Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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The Complex Nature of Lithium Extraction

A dynamic material flow analysis to understand supply constraints in the transition to electrified transport

Master's thesis in Industrial Ecology
Supervisor: Daniel Beat Müller
June 2022

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Preface

This thesis was carried out during the spring of 2022 as the final part of a journey to obtain a Master of Science in Industrial Ecology at NTNU. I would like to thank the IndEcol class and all those who supported me in Trondheim for an exciting and rewarding two years.

I feel extremely lucky to have had Daniel Müller as a tireless supervisor and mentor throughout my time as a student, as well as the commitment and patience of Romain Billy and Fernando Aguilar Lopez. I also had the privilege of being assisted by a large external team, whose insights added much to the work I have completed. I would especially like to acknowledge Evi Petavratzi, Kostas Georgitzikis, Jaco Huisman and Christian Rosenkilde for their valuable input.

I am writing my final words before submission on the traditional lands of the Secwépemc, whose resilience in the face of resource-motivated colonialism and devastation I am hopeful we can learn from moving forward.

Lastly, I would like to thank my family, who have put up with me ranting about lithium for far too long now, and without whose hard work I would not be where I am today.

Ukwikusha umutali, kubangilila
Do not delay a great undertaking

-Bemba proverb

Abstract

Many strategies for lowering emissions in the transportation sector largely rely on the conversion of the vehicle fleet from internal combustion engine (ICE) to lithium-ion battery (LIB) drivetrains. Despite the geologic abundance of lithium (Li), there are concerns that the extractives system may fail to expand at the rate demanded by the planned transition to battery electric vehicles (BEVs). This study aims to understand under what conditions a shortage could occur and suggests strategies for how such a situation could be avoided.

A dynamic material flow analysis with drivers from both supply and demand sides of the system was conducted for a model period of 2020-2050. A holistic assessment of geologic Li occurrences was performed which considered factors required for production, including environmental inputs, technology and social licensing. This was used to construct regional Li supply scenarios under probable, optimistic and breakthrough outlook conditions. Supply scenarios were aggregated at a global level and compared with different scenarios of Li demand. Recycling, lower vehicle ownership rates, smaller battery capacities and a shift away from Li-based chemistries were explored as possible interventions in the BEV demand system.

Based on the production factors considered, the scenarios revealed a large variation in future Li supply. Without any interventions, Li demand approaches or exceeds the limit of breakthrough supply for the entire model duration. Although all interventions were found to have a significant impact in reducing demand, no single intervention alone avoided the need for breakthrough supply levels. When all interventions were used together, demand was reduced to within probable supply levels by 2035, but still required optimistic supply levels before then.

This study found that without impactful changes through all aspects of the system, there is a significant risk that demand for EVs could outstrip supply in the short and long term. To mitigate this risk, the development of robust recycling systems and scalable, non-Li battery technologies is recommended. Significant and immediate investment is required to improve the technological, environmental and social performance of the Li extractives system. Finally, making deep changes to society’s reliance on the material intensive personal vehicle system should be considered.

Sammendrag

Mange strategier for å redusere utslippene i transportsektoren er i stor grad avhengige av utskiftning av biler fra forbrenningsmotor til litium-ion batteri. Til tross for den geologiske overfloden av litium (Li), har det vært usikkerhet rundt hvor mye og hvor raskt utvinningsystemet kan ekspandere. Denne studien tar sikte på å forstå under hvilke forhold en mangel på Li kan oppstå samt foreslå strategier for hvordan en slik situasjon kan unngås.

En dynamisk materialstrømanalyse med drivere fra både tilbuds- og etterspørselssiden av systemet ble gjennomført for perioden 2020-2050. En helhetlig vurdering av geologiske Li-forekomster ble utført, inkludert faktorer for produksjon som miljøinnsats, teknologi og sosial lisensiering. Disse ble brukt til å konstruere regionale Li-forsyningsscenarier under sannsynlige, optimistiske og banebrytende muligheter. Tilbudsscenarier ble aggregert på globalt nivå og sammenlignet med ulike scenarier for Li-etterspørsel. Resirkulering, lavere eierandeler av kjøretøy, mindre batterikapasitet og et skifte bort fra Li-baserte batterier ble utforsket som mulig intervensjoner i etterspørselssystemet.

Basert på produksjonsfaktorene som ble vurdert, avdekket scenariene en stor variasjon i fremtidig Li-tilførsel. Uten noen inngrep nærmer eller overskrider Li-etterspørselen grensen for banebrytende tilbud for hele modellens varighet. Selv om alle intervensjoner ble funnet å ha en betydelig innvirkning for å redusere etterspørselen, unngikk ingen enkelt intervensjon behovet for banebrytende tilbudsnivåer. Når alle intervensjoner ble brukt samlet, kunne sannsynlige tilbudsnivåer møte etterspørsel innen 2035, men krevde fortsatt optimistiske tilbudsnivåer frem til da.

Denne studien konkluderer med at uten gjennomgående og virkningsfulle endringer i alle deler av Li systemet er det en betydelig risiko for at etterspørselen for Li for elbiler vil overgå mulig tilbudsnivåer både på kort og lang sikt. For å redusere denne risikoen anbefales utvikling av kraftige resirkuleringssystemer samt skalerbare ikke Li baserte batteriteknologier. Det kreves betydelige og umiddelbare investeringer for å forbedre den teknologiske, miljømessige og sosiale ytelsen til Li-utvinningssystemet. Til slutt bør det vurderes å gjøre dype endringer i samfunnets avhengighet av det materialintensive personbilsystemet.

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1 Introduction

1.1 Background and Motivation

Lithium (Li) occupies the third position on the periodic table. Li was initially discovered in a Swedish petalite deposit in 1817. The following year brought the first preparation of Li as a stand-alone metal and, in 1854, the metal was prepared for the first time in gram-quantities. For many years Li had minor roles in pharmaceutical uses and as an additive, but interest and activity surrounding the material remained relatively dormant [1].

Li use began to accelerate during the events of the 20th century. Following World War I, Li-carbonate was required in large quantities for lead-based alloys in railway bearings. This industrial-scale availability allowed the ceramics industry to use Li-carbonate for imparting high mechanical strength and thermal shock resistance in their products [1]. During World War II, Li-hydroxide was used for CO_2 absorption in submarines and for Li-based lubricants. Li-hydride was also used as a convenient source of hydrogen [1], [2]. Li-isotopes were sought after during The Cold War due to their function in nuclear applications [1].

Global consumption of Li grew 700-fold during the 20th century [3], but demand exploded in the early 2000s after the rechargeable lithium-ion battery (LIB) made its way into portable devices at a large scale. Li is the lightest, most electronegative metal and has very low resistivity. These properties make it extremely desirable for battery applications [4]. The large share of emissions from the transport sector has led to a general acceptance that if there is an ambition to meet climate change targets, society's desire for personal automobiles can no longer be satisfied using the internal combustion engine (ICE). The LIB in its various forms is a key technology that has been chosen to replace the ICE by various governments, industries and the public. Global ambitions have now shifted up in scale from powering small electronics to powering personal mobility of all sizes in the form of the battery electric vehicle (BEV).

To achieve the technological transition to a decarbonized transportation system, a large increase in the supply of minerals will be needed. In some regions, it has been determined that the required mass of metals for EVs could amount to more than the requirements for all other renewable energy technologies combined [5]. The materials required for scaling up BEVs to the global fleet will depend on factors such as technological improvements and cathode chemistry choices – but all LIB chemistries will require a relatively constant mass of Li. Li is one of the raw materials that has never before been mined, processed and refined at near the quantities that will be needed [5], [6].

A range of groups, including the International Energy Agency (IEA) [7], auto manufacturers [8], [9] and industry experts [10] have become wary of a looming Li supply shortage. In addition, the spot price of battery grade Li chemicals rose by more than 400% between May 2021 and May 2022 [11]. This has stoked fears that the energy transition could be delayed by a simple lack of material availability.

In addition to the physical and operational barriers faced in supplying sufficient Li, there are the increasingly focused upon issues pertaining to the industrial system's interaction with the environment and society. The social and environmental implications of the anticipated rise in extraction of Li and other metals are often not considered in policy discussions and scenarios for the green energy transition. Extraction of Li and other metals has contributed to violent conflict, environmental degradation, population displacement, human rights violations and other adverse impacts [12].

A promise of the circular economy is that the linear supply chain involving primary production of materials will be replaced with a system where secondary sourcing (recycling) dominates material supply. This is problematic from a thermodynamic perspective for many materials, but with lithium a perfect storm of factors may make this unfeasible in the near future. Currently, less than one percent of lithium in products reaching end of life is recycled each year [6] due to the dissipative nature of non-battery Li applications and the prohibitive cost of recycling LIBs [4]. Additionally, just 0.51% of the global vehicle fleet is currently using BEV technology, meaning there is a huge deficit in available stock for future recycling [6]. Under the right conditions, Li can theoretically be recycled an infinite number of times [4] and recycling could become an important source in the future. However, the challenges at the intersection of technology and economics pertaining to recycling of Li mean that large inputs from secondary sources are not guaranteed even when large volumes of spent LIBs become available [13].

This is not to say that recycling cannot eventually become an important part of the system, but rather that our reliance on primary extraction will not disappear overnight. There is a need to understand how the various environmental, operational, social, and logistical constraints on extraction may affect the decarbonization of transportation. Society and the transportation system are relying on the ability of the Li system to keep up with their demands. It is important to question whether the system competently do this and what the consequences of our reliance on this one material might be.

1.2 Previous Studies and Knowledge Gaps

1.2.1 Geological Resources

The first building block for any analysis of Li is an understanding of its geological characteristics. Geological surveys have invested much effort into compiling relevant information on Li, as well as other metals and minerals that will be key for the energy transition. The United States Geological Survey (USGS) has published pieces that summarize the basics of lithium production and highlight supply options, both within the United States and globally, that could help fill the gap in the future [14], [15]. The British Geological Survey (BGS) has published similar information that focuses more on the British setting [4].

More in-depth geologic studies have gone further and sought to quantify the reserves and resources of Li. It should be noted that assessing Li availability is difficult and potentially unreliable due to differences in the way resources and reserves are accounted for [16]. The USGS publishes annual mineral commodity summaries which state their defined resources and reserves of Li [17]–[20]. Munk et al performed extensive work to understand global lithium brines [21]. Bradley et al created an exhaustive list of LCT pegmatite deposits, classifying them as either large or small [22]. Vikström et al [23] compiled and quantified potential resources from both brine and pegmatite sources to determine the minimum and maximum resources of Li. Evans has performed a large volume of work to understand and quantify global resources [24]–[26]. Yaksic and Tilton have quantified global resources and also estimated their production costs [27].

This body of work gives a relatively complete picture of the geologic availability of Li. However, this picture does not provide meaning without context of consumption and potential depletion of these resources.

1.2.2 Modelling Long-Term Depletion of Li

Many studies are indeed backed up by demand projections, which are compared with recoverable Li resources. Vikström et al concluded in 2013 that lithium availability could become an issue under certain EV penetration scenarios [23]. Greim et al concluded that Li must be effectively managed this century if exhaustion of economic resources were to be avoided [28] A dynamic model has concluded that supply may become an issue after 2050, but recognizes that prices may simply rise [29]. Additionally, this model predicts exhaustion of Li by the year 2400. Mohr & Mudd concluded in 2012 that ultimately recoverable resources (URR) are sufficient to last until 2200 [30],[31]. Kushnir and Sandén grouped resources into viable and marginal categories and estimated potential for output from mineral (non-brine) sources [32]. Ambrose and Kendall use a resource model that relies on geological characteristics and production costs to conclude that resources could likely meet demand through 2100, although lower grade and unfavourable deposits would be needed after 2050 [33]. Except for the Vikström and Greim studies, which use lower resource estimates, all studies point towards an abundance of lithium and no immediate concern surrounding depletion. More generally, Yaksic and Tilton argue that long-term depletion is not a concern, since at some point extracting Li from seawater will become economical [27]. Evans, commenting on availability, simply states that because of the miniscule production volumes in comparison to known resources, "Concerns regarding lithium availability for hybrid or electric vehicle batteries or other foreseeable applications are unfounded [24]."

1.2.3 System Understanding

Li in its geologic form, however, has value as a part of undisturbed nature and requires extensive value-added activity for inclusion in end-use products. What some of these studies often fail to account for are the complexities associated with putting a known geologic deposit through the various processes needed to turn it into these end-use products. The entire system must be up to the task of tackling the complexities of meeting this final demand, especially in terms of mining and extraction. Additionally, these simple supply and demand models often fail to account for the various waste flows that exist throughout the value chain.

Material Flow Analysis (MFA) can be used to place more focus on system understanding. MFA studies for Li have been undertaken with both regional and global system boundaries. The European Commission's material system analysis of battery-related materials [34] concluded that Europe currently has low involvement in most of the Li value chain. An MFA study performed for China [35] showed that, while the most important region for refined products, China was and would continue to be highly dependent on forms of imported Li. Global MFA studies [36], [37] have largely focused on trade between producing nations of different lithium products and give a solid understanding of the major players in the value chain. Though global studies, again the focus of these is largely fixated on China, with consideration only being given up until 2015. The BGS recently constructed a global MFA model for the year 2018 [38]. This provides an important update to show how some key dynamics in the system have changed since 2015. An attempt was made to improve upon this study with a more distinct differentiation between different lithium chemicals and compounds [39].

1.2.4 Criticality Analysis and Production Concerns

The labelling of a material as "critical" and quantifying this criticality has been undertaken formally by numerous governments worldwide. These lists are a useful starting point, but the methodology behind them needs to be understood. The EU list, for example, relies on two indicators: supply risk and economic importance [40]. These two indicators are calculated based on factors that only take into account the present-day system. For a material such as Li where the demand is expected not just to greatly increase, but to increase rapidly, examining the present-day system is not enough.

Potential issues regarding ramp-up times of new operations needed to meet this demand pose a challenge to the penetration of LIB technology. Mudd points out that a recent spike for Li demand was competently met by the ramp-up of Australian mining operations. Based on this, Mudd argues that when market conditions support a rapid response, the mining industry can meet the challenge [41]. However, there is still a need to re-examine conventional market response thinking for materials as we move into the quickly changing energy transition era. Historically, market studies have previously seen Li as low risk, although the idea of practical shortfalls that the market can not respond to is gaining traction [42]. Other research has been performed examining more specifically the potential for lithium supply risks. Li carbonate and Li hydroxide have been found to be subject to global competition in the LIB supply chain more so than other raw materials [43]. A study based on data from Bloomberg New Energy Finance (BNEF) found that there will be enough refined lithium until at least 2025, although Europe will likely face difficulty securing supply [44]. This, however, relies on a static prediction of supply and one assumed scenario of demand from EVs.

1.2.5 Environmental and Social Constraints

Mohr and Mudd declared that "As [the Li] market will be increasingly defined by the 'clean' image of electric vehicles, ensuring a clean chain of custody will be imperative for operations seeking both a future licence to operate (at site level) and licence to market (to final end uses of lithium) [30]." It is therefore important to understand what previous research has sought to identify hot spots and potential barriers to ensuring a "clean" supply chain.

There are measurable environmental impacts and social concerns surrounding Li extraction. These concerns have, to this point, been addressed in some capacity using Life Cycle Assessment (LCA) and Life Cycle Impact Assessment (LCIA). Recently, LCA studies have differentiated lithium production by location and by production route. Manjong et al constructed a parametric approach to understand global warming potential (GWP) of Li production under different extraction and energy supply conditions [45]. Research at the Argonne National Laboratory sought to understand the GWP and freshwater depletion of different lithium compounds produced from different production routes [46]. The Sustainable Minerals Institute (SMI) has developed a set of indicators for commodities, including Li, that identify environmental, social and governance risk factors at a global scale [47]. This is useful for identifying potentially contentious commodities. However, the metric aggregates all forms of lithium production into a single output. Social concerns are often highlighted from a qualitative lens. The most researched area is the Atacama in Chile [48],[49],[50], with limited extensive research in other areas. With the exception of the work from the SMI, there is very little quantitative data regarding social impacts from Li production.

In the extractives industry, social and environmental issues vary across both physical and human geographies. It is likely that many of the places where Li will be extracted in the future currently have no Li production. The interaction of the extractives industry with the environment and society is of great importance to the execution of projects, but there is limited research that has sought to quantify or compare the issues at different prospective Li extractive sites. The United Nations Framework for Resource Classification (UNFC) proposes an updated framework that considers social and environmental concerns when defining a resource [51], but the implementation of this is still in its infancy. Many issues and concerns are tied to mining in general and not just to Li. This expands the scope of considerations greatly, as there is a much larger body of research on the rest of the extractives industry. However, none of this proposes a suitable metric through which to understand how environmental and social concerns could limit Li production in the future.

1.2.6 Need for a Holistic Scenario-Based Analysis

The wide body of research on Li still leaves open a number of questions that have, to date, not been addressed. Though all of this research offers much valuable insight and information, there is no known previous work that combines all the necessary pieces to make an informed decision regarding whether or not a shortage of extracted Li could limit the transition to electric vehicles.

Past models have largely focused on technical or price inputs and have produced results that have turned out to be quite far off from today's reality. Kushnir and Sandén highlighted the importance of the time dimension and the institutional and social barriers that could affect this [32]. These considerations leave open the need for a scenario-based analysis that considers a wide range of factors and produces a wide array of outcomes to be explored further.

1.3 Research Questions and Tasks Completed

A rapidly evolving system such as what we are currently seeing with Li is not one that can be predicted or predetermined. The Li system in the coming years will likely be messy. There is therefore very little benefit gained in attempting to predict exactly what the system might look like.

This master's thesis aims to increase understanding of the potential evolutions of the Li industrial ecosystem and the consequences of these changes. With this motivation in mind, the following questions are addressed:

- How does the Li system react under different scenarios of future supply and demand?
- Could the Li extractives system fail to expand at the required rate?
- What interventions, strategies or alternatives can be taken to avoid this fate?
- What are the consequences of these strategies and the potential outcomes?

To answer these questions, a range of tasks was completed that covers a very wide breadth of the system from the present day and into the future.

First, building on the MSc project, the current state of the Li system was reviewed. Further research was performed regarding how the system could evolve from a technological standpoint. These considerations were integrated into a large-scale system definition. This larger system definition was then simplified down to a system definition that was still robust but could also be quantified with a higher degree of certainty. This served as a basis for the remaining tasks and was constructed and coded using Python.

The second step was to construct scenarios of future Li supply. This involved compiling the relevant lithium resources and grouping these resources into an appropriate and relevant framework. An extensive assessment of social, technical, economic and environmental issues facing each group of resources was performed. The potential resource output of each of these was estimated for three potential outlook scenarios.

The third step was to quantify the demand of the system. Historical data and assumptions were used to predict a static time series demand for non-EV end uses, such as phone batteries, stationary storage and pharmaceutical applications. The MATILDA model was used to construct different demand scenarios.

Finally, the supply and demand were combined to determine the market imbalance under the different scenarios. An analysis of the imbalances was performed and the consequences of different interventions was examined. A discussion aims to understand how the system could be improved and what the consequences of different system evolutions could be in the future.

2 Methodology

2.1 MFA System Approach

To properly understand and reasonably model the Li system, a solid understanding of industrial and environmental realities is required. To achieve this the method of Material Flow Analysis (MFA) was chosen. A key principle of MFA is the mass balance of all processes in the system, and therefore of the entire system as a whole. This is outlined in greater detail in the Handbook of Material Flow Analysis [52]**.**

This method provides several advantages not always present in traditional supply-demand balance exercises. First, the system is accurately broken down into the different methods and routes of production and consumption. This allows for use of data from different sources that are reported in different ways. Data does not have to be aggregated into one lump sum on both supply and demand sides. Second, each process includes a transfer coefficient representing the recovery and consequential wastes of the material from that specific process. This is crucial as losses through system processes can have a substantial effect on the overall availability of the material.

Dynamic MFA allows for the quantified modelling of these systems over time. This provides a basis for an examination of how the system could change and evolve in the future. The Li system described here was modelled for the period of 2020-2050.

2.1.1 Initial System Construction

The construction of the system definition was guided by two key goals. The first was to obtain a snapshot that accurately approximates the reality of the Li value chain on a global scale. The second was to have a system that could both be quantified and modelled with accuracy and, again, a reasonable degree of potential reality.

To understand the Li system in its entirety, an effort was made to illustrate the production and consumption of Li at high granularity (Figure 1). This was previously done as a part of the MSc project [39]. The figure was slightly modified to capture new aspects of the system, such as new extraction methods and recycling. Certain aspects in chemical production processes were also aggregated.

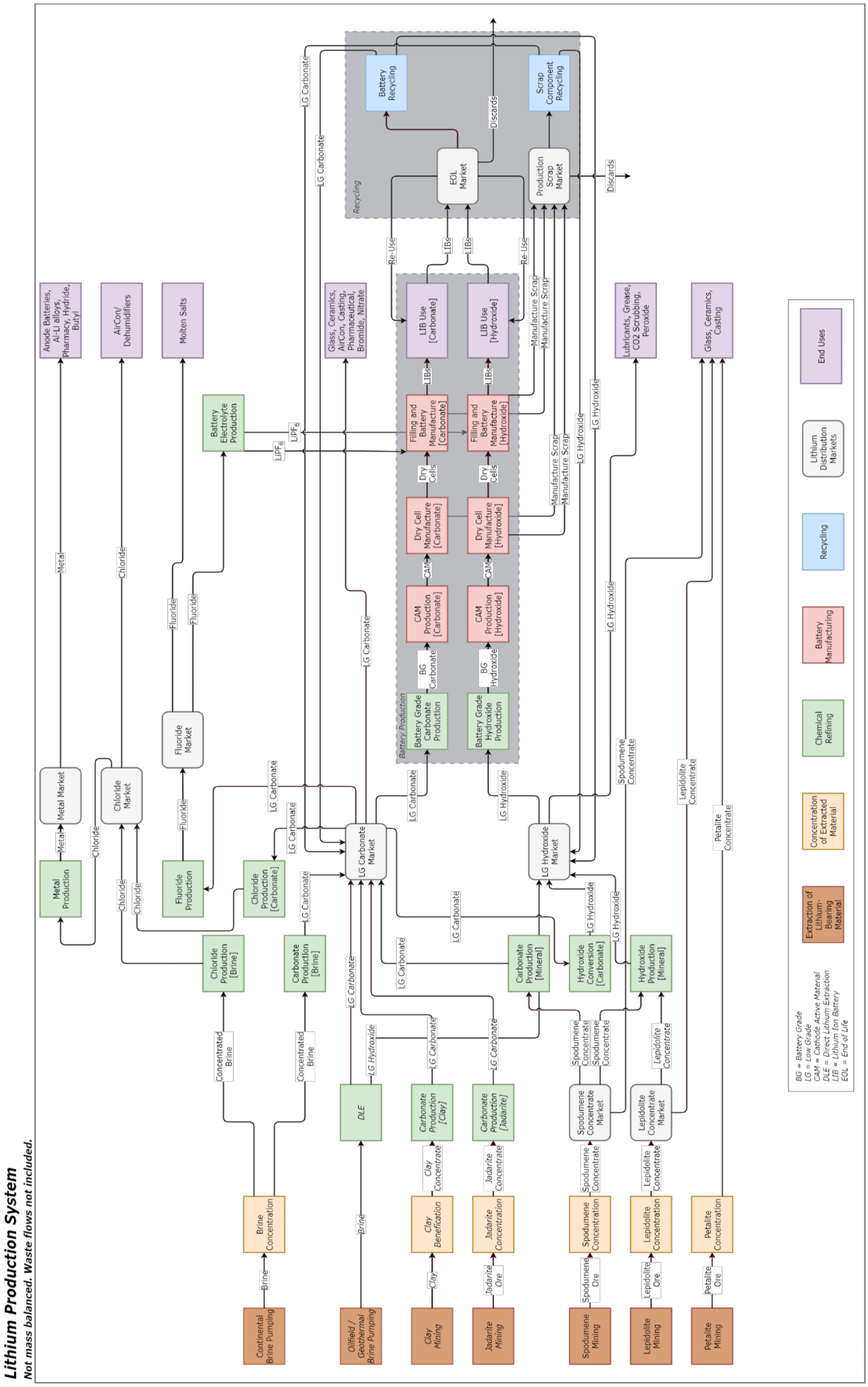

Figure 1: The Lithium Production System, from extraction to end of life. All flows represent Li-containing materials. Flows and processes that are not present in today's system are italicized.

This figure gives a good representation of reality (with the exception of waste flows, which are excluded). However, a system of this detail is nearly impossible to quantify based on current available data. Furthermore, the chances of modelling this system with any accuracy in the future are very slim. A simplified system definition was therefore constructed that could be used for quantification and modelling work (Figure 2).

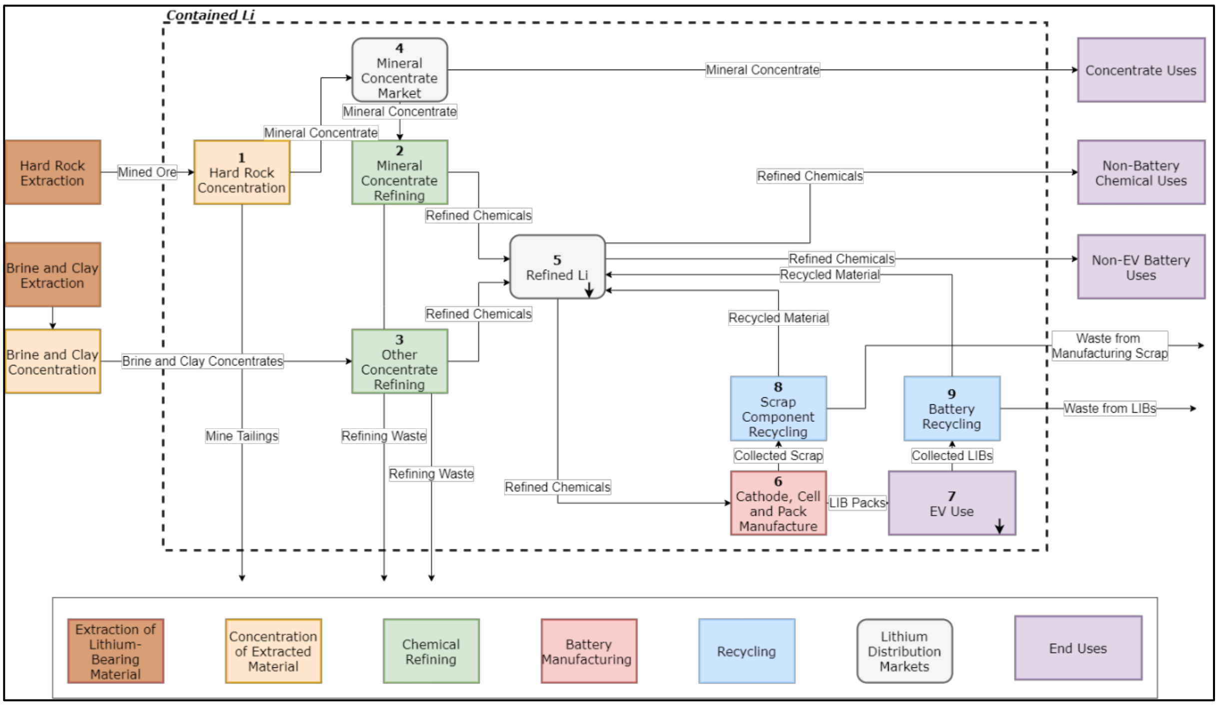

Figure 2: Model System Definition. Key aspects of the production system in Figure 1 were aggregated here to construct a system that was realistic and quantifiable for the tasks carried out in this study.

A description of each process can be found in Table 1. Processes not included within the system boundaries but deemed relevant influences on the system are also displayed and described.

Table 1: Model Process Descriptions

Process Number	***Process Name***	***Process Description***
1	Hard Rock Concentration	Mineral processing that takes mined ore as an input and produces a marketable mineral concentrate as an output. Mine tailings is produced as a by-product.
2	Mineral Concentrate Refining	A group of chemical processes that takes a mineral concentrate input and transforms this into a refined chemical. Li is lost throughout the various sub-processes to waste.
3	Other Concentrate Refining	A group of chemical processes that takes a brine or a clay concentrate input and transforms this into a refined chemical. Li is lost throughout the various sub-processes to waste. Brine and clay feedstocks will require completely different physical processes; for data simplicity they are grouped together here.
4	Mineral Concentrate Market	Market process designed to separate mineral concentrates into a) material to be sold and used in the manufacture of final

		products, such as glass and ceramics, or b) material sent to chemical refining.
5	Refined Li Market	Market process designed to take refined Li from various sources and send it to various sectors that use Li chemicals. No distinction is made between the various grades of chemicals (e.g. battery grade, technical grade, pharmaceutical grade).
6	Cathode, Cell and Pack Manufacture	A group of processes that take raw materials as inputs and manufacture a useable and saleable LIB pack. This includes synthesis of cathode active material, cathode production, cell manufacture and battery pack assembly.
7	LIB Use	The use phase of electric vehicles. Vehicles enter this process at the beginning of their life, leaving the process at the end of their lifetime. This process includes modelling work from the MATILDA model that was calculated and designed separately. For this modelling work, the parameters are modified based on an understanding of the underlying calculations to create different scenarios.
8	Scrap Component Recycling	Recycling processes used to recover metals from scrap components and materials from manufacturing processes. This could include pyrometallurgical, hydrometallurgical or direct recycling. These various methods will recover different amounts of Li.
9	Battery Recycling	Recycling processes used to recover metals from end-of-life batteries from electric vehicles. This could include pyrometallurgical, hydrometallurgical or direct recycling. These various methods will recover different amounts of Li.
-	Hard Rock Extraction	Outside system boundary; The extraction of economic ore from the geologic earth.
-	Brine and Clay Extraction	Outside system boundary; The extraction of brines and clays from the geologic and hydrogeologic earth.
-	Brine and Clay Concentration	Outside system boundary; Concentration of clays and brines into a material that can undergo chemical refining.
-	Concentrate Uses	Outside system boundary; End-use applications of mineral concentrates that exert demand on the mineral concentrate market.
-	Non-Battery Chemical uses	Outside system boundary; End-use, non-battery applications of Li chemicals that exert demand on the refined Li market.
-	Non-EV Battery Uses	Outside system boundary; End-use, non-EV battery applications of Li chemicals that exert demand on the refined Li market.

These processes are a very high-level aggregation of the actual activities occurring within the system. In addition, model processes such as Other Concentrate Refining might include completely different physical processes depending on the different types of feedstocks used as an input. This aggregation is meant to approximate the data outputs using the data inputs available.

2.1.2 Quantification - Transfer Coefficients

Many of the processes are accompanied by transfer coefficients, which are used in conjunction with mass balancing to quantify the system. The transfer coefficients are displayed in Table 2.

Table 2: Transfer coefficients. Values are based on literature, assumed values and the MATILDA model described later in the methodology.

Transfer Coefficient	***Description***	***Value***	***Source***
kx_1	Recovery rate of Li in beneficiation of hard rock ores	0.66	[53]
kx_2	Recovery rate of Li based on refining of mineral concentrates	0.9	[53]
kx_3	Recovery rate of Li based on refining of concentrated brines and clays	0.9	Assumed
kx_6	Recovery rate of Li during the manufacturing process from chemical input to complete battery pack output	0.9	[54]
kx_8	Recovery rate of Li during recycling of manufacturing scrap	Dynamic – changes based on demand scenario	MATILDA Model
kx_9	Recovery rate of Li from recycling of end-of-life LIBs	Dynamic – changes based on demand scenario	MATILDA Model

Transfer coefficients k_{x1} and k_{x3} do not actually influence the overall comparison of supply and demand. These transfer coefficients are instead useful for calculating the total waste outflows in the form of process waste and mine tailings. Both values can vary significantly across different facilities, feedstocks and stages of production. The values here are the best approximations available for a high-level analysis of the system.

The outputs from system processes that flow to Process 5 are assumed to include *all* refined Li products, regardless of grade (e.g., battery, technical, pharmaceutical). The losses of refining to different products and at different purities likely differ, but the approximation here is used to include all refining from concentrate to useable chemical additive.

The value of manufacturing scrap, k_{x6} is highly speculated on. The recovery value is likely much lower than stated here during the ramp-up phase of manufacturing facilities and could be higher once production becomes more streamlined [54]. The value here is an approximation that assumes good recovery and efficiency in manufacturing processes while being somewhat negatively impacted by the ramp-up of new facilities.

2.1.3 Quantification – Flows

With the processes defined and the accompanying transfer coefficients settled, the strategy for quantifying the system can be determined. Each flow and the way in which it is calculated is displayed in Table 3. Additionally, the variability of each flow over different changes in scenarios is given. Some flows contain constant time-series values, regardless of scenario choice. Some flows are sensitive to a change in demand scenario. Some flows are sensitive to a change in supply scenario.

Table 3: Flows. Each flow is calculated by use of transfer coefficients, mass balance or from external inputs. The scenario analysis conducted on both supply and demand sides in this study can cause certain flows to vary.

Flow	***Flow Description***	***Calculation Method***	***Variability With Scenarios (Supply/Demand/None)***
$A_{0\text{-}1}$	Mined ore to be sent to mineral beneficiation, commonly known as "Run of Mine (ROM)"	Calculated based on transfer coefficient k_{x1}	Supply
$A_{0\text{-}3}$	Concentrated clay and brine material	Primary supply input data	Supply
$A_{1\text{-}4}$	Processed mineral concentrate	Primary supply input data	None
$A_{4\text{-}2}$	Mineral concentrate sent to chemical refining	Mass balance	Supply
$A_{2\text{-}5}$	Refined Li from mineral concentrate feedstock	Calculated based on transfer coefficient k_{x2}	Supply
$A_{3\text{-}5}$	Refined Li from brine or clay feedstock	Calculated based on transfer coefficient k_{x3}	Supply
$A_{4\text{-}0}$	Mineral concentrate sent for non-chemical end-use applications	Calculated demand from mineral concentrate end-uses	None
$A_{5\text{-}0(i)}$	Refined chemical to be used in non-battery applications	Calculated demand from non-battery chemical uses	None
$A_{5\text{-}0(ii)}$	Refined chemical to be used in non-EV battery applications	Calculated demand from non-EV battery uses	None
$A_{5\text{-}6}$	Refined chemical to be used in LIB production for EVs	Calculated based on transfer coefficient k_{x6}	Demand
$A_{6\text{-}7}$	Finished battery packs for use in EVs	Calculated demand based on output from the MATILDA model	Demand
$A_{6\text{-}8}$	Manufacturing scrap from CAM, cathode, cell and pack production	Calculated based on transfer coefficient	Demand
$A_{7\text{-}9}$	End-of-life batteries from EVs	Calculated outflows of end-of-life LIBs from EVs based on output from the MATILDA model	Demand

$A_{8\text{-}5}$	Recovered chemicals from the recycling of manufacturing scrap	Calculated based on transfer coefficient kx_8		Demand
$A_{9\text{-}5}$	Recovered chemicals from the recycling of end-of-life LIBs	Calculated based on transfer coefficient kx_9		Demand
$A_{1\text{-}0}$	Waste from mineral beneficiation, commonly known as tailings	Waste flow calculated based on transfer coefficient kx_1	Supply	
$A_{2\text{-}0}$	Waste from chemical refining of mineral concentrates	Waste flow calculated based on transfer coefficient kx_2	Supply	
$A_{3\text{-}0}$	Waste from chemical refining of concentrated brines or clays	Waste flow calculated based on transfer coefficient kx_3	Supply	
$A_{8\text{-}0}$	Waste from recycling of manufacturing scrap	Waste flow calculated based on transfer coefficient kx_8		Demand
$A_{9\text{-}0}$	Waste from recycling of end-of-life LIBs	Waste flow calculated based on transfer coefficient kx_9		Demand

Flows that were calculated externally (i.e. not from mass balance or transfer coefficients) are explained in more detail later as a part of either supply or demand inputs.

2.1.4 Calculation of Supply and Demand

Quantification of the system as described above intentionally results in a mass-balance inconsistency around process 5, the market for refined Li. No attempt is made to reconcile the system in a mass-balanced fashion. This is done in order to understand the potential surplus or deficit around processed Li in the future. After quantifying the system for a given scenario, the supply of and demand for *primary* (i.e. mined) Li is calculated (Table 4). The supply and demand for mineral concentrates in end-use products is also included here, although this remains constant across scenarios and is assumed to always be equal. Li available from recycling is subtracted from the overall demand, rather than adding to the overall supply. This keeps the focus on the extractives sector rather than on the total availability from all sources.

This calculation is done year by year, with no stock buildups that carry over in either of the market processes. The assumption with the absence of stocks is that stock buildups will not be built up to such large levels that they could have an outsized impact on the overall supply-demand picture. The robustness of this assumption is tested later.

Table 4: Calculation of Supply and Demand. Calculations center around the two market processes, Process 4 and Process 5.

Flows to Calculate Supply		***Flows to Calculate Demand***	
Flow	***Flow Name***	***Flow***	***Flow Name***
A_{4-0}	Mineral Concentrate	A_{4-0}	Mineral Concentrate
+		+	
A_{3-5}	Refined Li	$A_{5-0(i)}$	Refined Li
+		+	
A_{2-5}	Refined Li	$A_{5-0(ii)}$	Refined Li
=		+	
Total Primary Lithium Supply		A_{5-6}	Refined Li
		-	
		A_{8-5}	Recycled Li
		-	
		A_{8-5}	Recycled Li
		=	
		Total Primary Lithium Demand	

2.2 Demand - Non-Vehicle Lithium Use

With the construction and the quantification methodology of the system understood, as well as the overall goal of determining imbalances between supply and demand, the next step is to calculate the input flows over the duration of the time series. In the case of non-vehicle Li demand, these values were calculated as single time series that do not vary under different scenarios.

2.2.1 Non-EV Battery Uses – Portable Electronics and Stationary Storage

The focus of this thesis is on examining the impact of EVs. Because of this, conservative and general approximations were placed on non-EV battery uses, namely stationary storage and portable electronics.

LIBs for portable electronics have experienced a considerable spike in demand this century, to the point where they already in widespread use across many consumer, industrial and other sectors. Although this demand will likely increase in some capacity, the general assumption is that the growth in annual demand for Li in portable electronics will not experience a significant uptick in the future. Additionally, batteries in portable electronics and the resulting required lithium inputs are much smaller than for LIBs in EVs, meaning that variations in growth would likely not have an outsized impact on overall future demand.

The situation with regards to stationary storage is much different. This sector is, like EVs, rapidly evolving. While LIBs have become the technology of choice for EVs and portable electronics, stationary storage solutions are not constrained by energy density characteristics that make LIBs so desirable for portable applications. Other battery technologies, such as sodium-ion, zinc-ion and vanadium flow could also be used heavily in this sector. Stationary energy storage is also possible with a plethora of non-battery technologies, such as pumped hydro. Despite this, energy storage will present a major challenge in the energy transition and substantial growth from all technologies can be expected.

LIB use for stationary storage applications could largely depend on the price of raw materials, in particular Li, and how the overall cost stacks up against other major energy storage options. This, therefore, somewhat fits in with the purpose of the modelling exercise. If there is a major shortage of mined materials, the price of LIBs for stationary storage will likely go up, meaning that other energy storage methods will become more desirable. If prices remain low, this could encourage widespread adoption of LIBs for stationary storage solutions.

With this in mind, it was assumed that growth for both of these sectors would increase in line with growth rates since 2015. Demand for all battery uses is given by the USGS for the year of 2018 [21]. Reported 2018 values of portable and stationary energy storage were 31% and 5%, respectively [55]. Cumulative annual growth rates (CAGRs) for portable electronics were taken from Yaksic and Tilton [27], with rates of 10% until 2028 and 3% until 2050. In the case of Li in stationary storage, a large CAGR of 10% was assumed for every year from 2018 to 2050. This growth rate should not be looked at as a prediction or even as a likely possibility, but as a minimum baseline value for demand that could greatly increase depending on market and technological conditions. Again, modelling potential volumes of LIBs used for energy storage is a large task outside the scope of this project, but it is safe to assume at least a small baseline value moving forward.

Recycling was not considered for any of these options. With portable electronics, the assumption is that the recovery of small amounts of Li is uneconomical and, in any case, of quite small volumes and suffering from low collection rates. In the case of ESS, it is assumed that batteries put into use will be repaired and used in some capacity for the entire model duration.

2.2.2 Non-Battery Uses

As the growth of non-battery Li demand has seen much less activity in recent years, it is simpler to understand its growth than it is to estimate the rapidly growing LIB sector. Historical demand data from the USGS was taken for non battery uses from 2011-2021. Linear regressions was then performed to project yearly demand to 2050 (Figure 3).

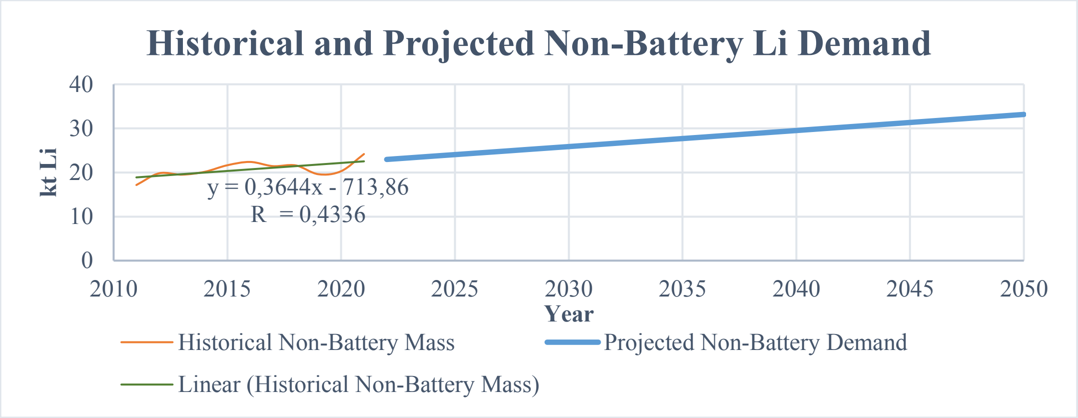

Figure 3: Historical and Projected Non-Battery Li Demand. Demand projections were obtained by performing linear regression on historical data.

This does not distinguish between demand for refined Li chemicals and unrefined mineral concentrates A constant split of 25% for concentrates and 75% for chemicals was used. This assumed that while uses for concentrate are significant, non-battery chemical applications require greater volumes.

2.3 Demand Scenario Construction – MATILDA Model

2.3.1 Background

The values for the flow $A_{6\text{-}7}$, the key demand driver of the system, are given by the Material Demand and Availability (MATILDA) model. MATILDA is part of a currently unpublished work that uses a parametric approach to model future scenarios of the personal vehicle system. The result contains a material layer of the global vehicle stock for batteries, which gives the mass of materials for each year for the in-use stock (M_7), vehicle inflows ($A_{6\text{-}7}$) and vehicle outflows ($A_{7\text{-}9}$).

2.3.2 Adjusted Parameters

The inputs into this model include many parameters that can be modified to create different scenarios. The parameters considered for the purpose of demand scenario building here are given in Table 6.

Table 5: MATILDA Model Parameters. A more complete description of these parameters can be found in the supplementary information.

Parameter	***Options***
Vehicle Stock	Low, Medium, High
EV Penetration	Low, Medium, High
LIB Chemistry	BNEF, Next Gen BNEF, Li Free
Battery Size	Shift to Small, Constant, Shift to Large
Recycling Rate	Pyrometallurgical, Hydrometallurgical, Direct
Reuse	No Reuse, All Reuse, LFP Reuse Only

Two new options for LIB Chemistry were custom designed for this study. Taking the existing BNEF option, Li-air and Li-sulphur chemistries begin to capture market share in 2030, increasing this share until they each hit 30% in 2040. This creates the "Next Gen BNEF" chemistry option. Then taking this distribution as a baseline, chemistries that do not use Li (e.g. sodium- and zinc-based chemistries) start capturing market share in 2025, increasing this share until they hit 50% in 2035. This creates the "Li Free" option (Figure 4). The Li Free chemistry share represents a future where a more diverse technology mix (LIB, Li-anode and non-Li based) serves the needs of the EV system.

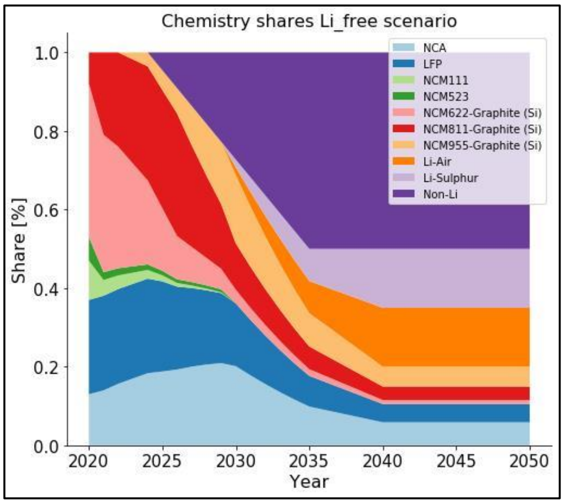

Figure 4: The Li Free Chemistry Mix. This follows the standard BNEF chemistry distribution until 2025, when non-Li based chemistries enter the system, while Li-sulphur and Li-air chemistries enter the system in 2030.

A complete summary and explanation of these parameters and the modifications made for the purpose of demand calculations in this model is given in section 1 of the supplementary information.

2.3.3 Compilation of Vehicle Demand Scenarios

With the background of each system input understood, parameters can be chosen to construct scenarios of Li demand. The wide range of input options from the vehicle model leaves a larger range of output options, even with the options restricted as stated above. Because of this, it was necessary to organize the scenarios in a strategic manner. The choice of inputs to construct nine scenarios is shown in Figure 5. Input options were split into two categories: technological and societal. Battery chemistry and recycling method were categorized as technological input parameters, while vehicle stock and vehicle size were categorized as societal input parameters. Parameters are not completely independent of either category. For example, battery chemistry and battery size are somewhat dependent on one another, while a lower vehicle stock could be dependent on future innovations in AI and rapid transit. However, it is assumed here that the parameters rely heavily on either technological innovation or on social change.

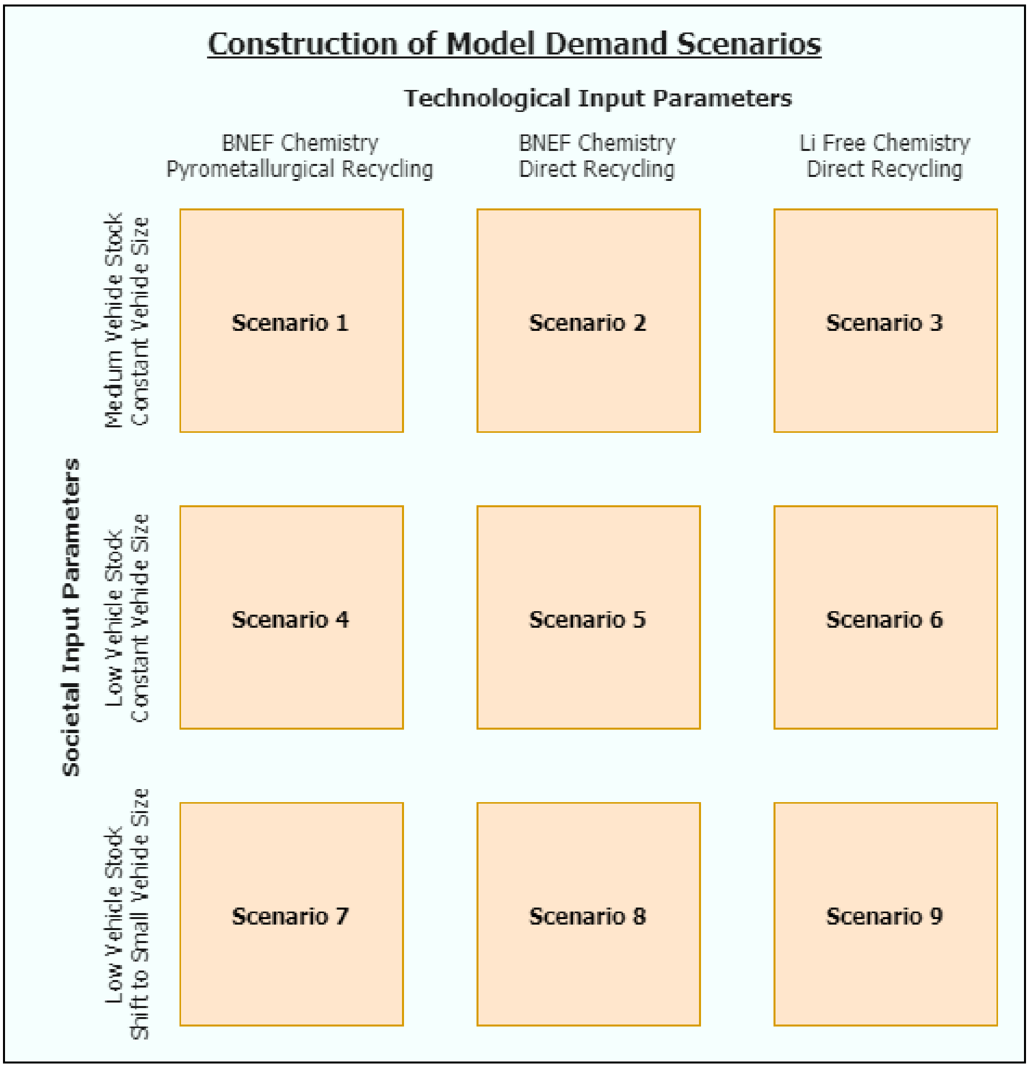

Figure 5: Construction of Model Demand Scenarios. Starting from Scenario 1, interventions are made through a combination of technological changes (moving left to right) and societal changes (moving top to bottom).

For all scenarios, a medium EV penetration is assumed, a rate which MATILDA bases on the IEA's Sustainable Development scenario. All scenarios assume that no LIBs are reused and that all are made *available* for collection and recycling.

Scenario 1 is based on today's observed situation. Technologically, almost all EVs are powered by LIB chemistries and pyrometallurgical recycling sends essentially all Li to waste. Socially, a medium vehicle stock and constant vehicle size assume no major changes based on present conditions.

Moving one step along the x-axis assumes that direct recycling becomes widespread for recovery from both manufacturing and vehicle scrap. Moving to the final position assumes that Li-free chemistries capture a large share of the market, in addition to implementation of direct recycling systems.

Moving one step along the y-axis assumes that the vehicle stock is lowered. Moving down to the final position assumes that there is both a low vehicle stock and that those vehicles have a reduced battery size.

2.4 Supply Scenario Construction – Extracted Li

To complete the system quantification, scenarios for the supply flows $A_{1\text{-}4}$ and $A_{0\text{-}3}$ had to be created. At an early stage in the research process, it was concluded that the number of potential factors determining Li supply made using quantitative inputs to model a predicative output unreliable. At best, doing this would far exhaust the time and resources available, while at worst the results would be oversimplistic and fail to account for the various complexities of the input factors.

Because of this, the methodology for creating the supply scenarios revolved around a scenario-based analysis that was constructed with broad inputs with both quantitative and qualitative considerations. This attempts to find a unique way to consider a multitude of factors in a somewhat robust fashion. The goal is to provide a range of possibilities that capture, with the best effort, potential future realities.

The supply scenario construction consisted of five main parts:

(1) Understand, at a broad level, what factors impact mined production of Li
(2) Deconstruct the global system into different regions that share similar characteristics

(3) Understand how the various factors could apply to each of the regions
(4) Use the listed concerns and available numerical data to create scenarios for each region
(5) Compile the regional scenarios to understand scenarios at a global level

2.4.1 Understanding the Required Inputs for the Lithium Supply System

The focus of this Li supply analysis is on the extraction and concentration stages of the value chain. In practice, of course, concerns cannot be isolated so simply. Refining of concentrates is heavily dependent on the geology and mineralogy of the original deposit and feedstock. Refining during direct lithium extraction (DLE) and from unconventional mineral sources, such as petalite and lepidolite, could hinder the economics of mining and extraction. There is a strong desire amongst mining nations to move downstream and add more value to their product before exporting it, which could limit free movement of supply in the future.

However, for the purpose of this study, an attempt was made to limit considerations to the extraction stage as much as possible. This might seem counter-intuitive, since in the model setup the supply is assessed at the stage where Li is processed and sent to market. The assumption here is that the key supply bottleneck will occur at the extraction site, where the greatest diversity of factors could limit future production. While refining capacity may be of concern to specific regions for supply security reasons, it is assumed that in general it is much quicker to increase refining capacity than it is to increase mining capacity. Additionally, mining must happen at a specific area defined by geology. Refining locations are also determined and influenced by several factors – it is not simply desirable to build a refinery anywhere. However, examining this at a global scale requires an entirely different analysis, with determining location made extremely difficult by not having geological limitations.

The issues that were initially considered as potential determinants when assessing current and future extraction are visualized in Figure 5. Subpar conditions in any of the areas below may lead to a project being delayed, cancelled or operated at a reduced capacity. A more detailed explanation of these inputs and the different factors considered is given in section 2 of the supplementary information.

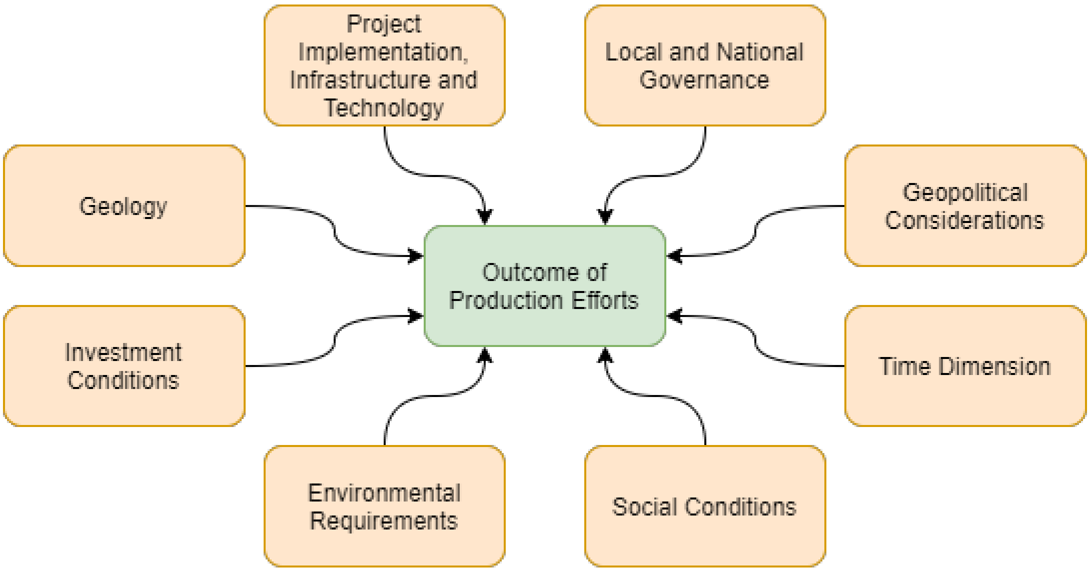

Figure 6: Input Requirements for Li Production. These requirements were considered during the construction of the supply scenarios.

2.4.2 Identification of Locations and Regional Groupings

With the risks and requirements for increased supply known, the next step was to outline geographic boundaries within which to explore these concerns. To simplify the large task of exploring every single area with identified Li resources, the Global Li mines, deposits and occurrences map [56] from the BGS was used as a starting point. This includes 88 locations that are either operating mines, projects in development or deposits and occurrences that have been deemed by the BGS to be relevant.

From this list, the 88 locations were split into ten different groupings based on a) continent and b) deposit type (Table 6). A similar approach has been taken in previous Li modelling work [30], [31], albeit with different boundaries. The advantage of this is that it still allows each deposit to be examined individually, but also allows for analysis of the entire region, which may share similar characteristics in terms of social attitudes, environmental issues and governance.

Table 6: Supply Groupings. All relevant Li deposits are covered, with each grouping based on geography and geology.

Grouping Name	***Description***
Africa Hard Rock	Hard rock deposits on the African continent.
Australian Hard Rock	Hard rock deposits on the Australian continent.
Asian Brines	Brine projects on the Asian continent and in Russia.
Asian Hard Rock	Hard rock projects on the Asian continent and in Russia.

European Hard Rock	Hard rock projects on the European continent, excluding Russia.
European New Tech	Geothermal Brine projects on the European continent, excluding Russia.
North American Hard Rock	Hard rock projects on the North American continent.
North American New Tech	Continental, geothermal and oilfield brine and clay projects on the North American continent.
South American Brines	Brine projects on the South American continent.
South American Hard Rock	Hard rock projects on the South American continent, including projects with sedimentary geology.

This grouping method is not without its drawbacks. The “New Tech” groupings include projects that will largely rely on DLE methods to obtain Li from geothermal and oilfield brines. DLE actual refers to a group of technologies that can be applied in various ways. This “new technology” could be very applicable to continental brine operations in South America and Asia, with DLE either replacing or acting as a supplement to conventional evaporation ponds (as is already the case in some locations). The “New Tech” groupings should not, therefore, be misinterpreted as being the only two groupings where DLE technologies could be applicable. The one continental brine project in North America included on the list, at Silver Peak, was grouped under the New Tech category to avoid having a separate category for one single, small operation. Indeed, DLE methods could also be applied to increase production here.

The way in which data is generally reported also played a role. At hard rock mine sites, targeted or actual production values are stated by sources in terms of mineral concentrate. At most other operations, these values are given in mass of produced chemicals, in terms of lithium carbonate equivalent (LCE). Because of this, clay projects in North America were grouped under the New Tech category. The similarities between clay mining and hard rock mining are much greater than clay mining and DLE from geothermal/oilfield brines. It could be argued that new clay projects face similar hurdles as new hard rock mining projects. However, because of the data reporting conditions they were grouped under the North American New Tech grouping.

Jadar in Serbia and Falchani in Peru are both volcano-sedimentary deposits. Despite their strong relation to clays, also considered volcano-sedimentary deposits, Jadar and Falchani are grouped into the “Hard Rock” categories within their respective continents.

The analysis was not limited to only the locations on the map. During the research process, other deposits that were found to be of potential significance were added. These include the geothermal and oilfield brine occurrences in Western Canada (North American New Tech), Manono-Kintola Tailings in the DRC (African Hard Rock) and Russian pegmatite deposits in Siberia and on the Ksola Peninsula (Asian Hard Rock).

2.4.3 Key Concerns by Grouping

With global geologic Li broken down into these ten groupings, resources could be examined in more detail. This was done using the factors outlined in section 2.4.1. The process behind this was ongoing and considered information from a wide scope of sources. Notes were made and eventually compiled into a summary of issues that could apply to the specific locations and to entire regions. A summary of these key concerns can be found in section 3 of the supplementary information.

The goal of this part of the process was aimed at being purely qualitative in nature. Because of the high variability of many of the factors, it was deemed unreasonable to "score" the regions or projects based on the findings. The point of this exercise was instead to gain a relatively complete knowledge of the situation at each location and to use this to inform scenario building later.

2.4.4 Three-tiered Outlook Classification

All these inputs are, again wide in scope. Many have a qualitative nature that spreads into the realm of social science. Those that are more measurable are often surrounded by large uncertainties, for example deposit grade and reserve/resource levels. In any case, there are a plethora of different factors that each contain a huge amount of information. With this in mind, the goal of using different "tiers" of potential supply was to avoid predicting what the supply would most likely be, and to instead create different levels of supply based on different supply system conditions.

Three levels of confidence were chosen for the scenarios: Probable, Optimistic, and Breakthrough.

- **Probable** – The lowest level of extraction. Based on the current situation and assumes largely unchanged system conditions in the future. This is largely characterized by uneven attitudes towards resource extraction, insufficient social licensing and low improvements in technology or environmental mitigation. In addition, it assumes governance and geopolitical challenges that hinder production.

- **Optimistic** – Increased level of extraction. A greatly increased societal acceptance of resource extraction, where social licensing is given more due diligence and hostility towards resource projects decreases. Existing technologies are moderately improved upon and these technologies becomes economically viable for adoption at a larger scale. Government support for increased extraction largely allows the extractives sector to build and execute projects according to plan.
- **Breakthrough** – Dramatically increased level of extraction. This primarily relies on technological breakthroughs that allow for economic extraction at scale. Technology decreases the total environmental inputs required for extraction. Social concerns are diminished due to both reduced impacts of extraction and a dramatic push to conduct proper social licensing. Unprecedented financial and technical support from governments sees projects constructed quickly and supply reaching the market in a timely manner.

The issues and barriers faced by each region were then examined to try and understand how they could be classified into these different confidence levels.

Projections and hard production numbers, of course, had to be sourced moving forward. A wide range of sources were used. The largest source of planned production values come from companies with production rights to the undeveloped deposits considered, as well as from currently producing companies. Company information included pre-economic studies (PEAs), resource assessments, prefeasibility studies (PFS) and definitive feasibility studies (DFS), as well as generic information found publicly on company webpages and announcements. In addition, specific country predictions could be found from industry sources. Less reliable sources, such as reported country targets from news articles, were also considered.

Finally, region-specific concerns, the obtained data and the defined confidence levels had to be brought together to obtain the hard values for the supply scenarios. Because of the vast differences between different continents and deposit types, this was done differently for each of the ten groupings. The general strategy for quantifying each region is found in Table 7.

Table 7: Quantification Method by Grouping. Specific Sources and links can be found in both the supplementary excel file and supplementary information.

Grouping Name	***Description***
Africa Hard Rock	Company studies used to estimate production and production start times for each listed deposit. Deposits in preliminary stages of assessment or without known commercial operations were given small production values and later production start dates. The number of deposits chosen to produce a product varied by scenario.
Australian Hard Rock	Individual projects were not assessed. Recent production was considered as a base and a CAGR for each scenario was chosen, based on reports and market studies assessing future supply.
Asian Brines	Individual projects within China were not assessed. Recent production was considered as a base and a CAGR for each scenario was chosen, based on reports and market studies assessing future supply. Production from projects outside of China was included in certain scenarios.
Asian Hard Rock	Individual projects within China were not assessed. Recent production was considered as a base and a CAGR for each scenario was chosen, based on reports and market studies assessing future supply. Production from projects outside of China was included in certain scenarios.
European Hard Rock	Company studies used to estimate production and production start times for each listed deposit. Deposits in preliminary stages of assessment or without known commercial operations were given small production values and later production start dates. The number of deposits chosen to produce a product varied by scenario.
European New Tech	DLE production assigned values for optimistic and breakthrough scenarios based on potential projects and the assumption that DLE production in Europe will be less the DLE production in North America.
North American Hard Rock	Company studies used to estimate production and production start times for each listed deposit. Deposits in preliminary stages of assessment or without known commercial operations were given small production values and later production start dates. The number of deposits chosen to produce a product varied by scenario.
North American New Tech	Clay projects in Mexico and the USA were included. Additionally, various volumes of production from DLE brine sources were included for the optimistic and breakthrough scenarios.

South American Brines	Individual projects were not assessed. Recent production was considered as a base and a CAGR for each scenario was chosen, based on reports and market studies assessing future supply.
South American Hard Rock	Company studies used to estimate production and production start times for each listed deposit. Deposits in preliminary stages of assessment or without known commercial operations were given small production values and later production start dates. The number of deposits chosen to produce a product varied by scenario.

More detailed information about assumptions can be found in section 4 of the supplementary information. Specific data sources can be found in the supplementary excel file.

In the construction of these scenarios, reserves and resources were not explicitly considered. However, once scenarios were constructed, the cumulative production were compared against USGS listed resources. None of the production scenarios have cumulative production that outstrips resources in any specific region.

3 Results

3.1 The Current System

The quantified system for the year of 2021 is shown in Figure 7. 2021 was the last year for which independently sourced supply and consumption data could be obtained. The exception to this is flow $A_{7\text{-}9}$, which was sourced from the MATILDA model.

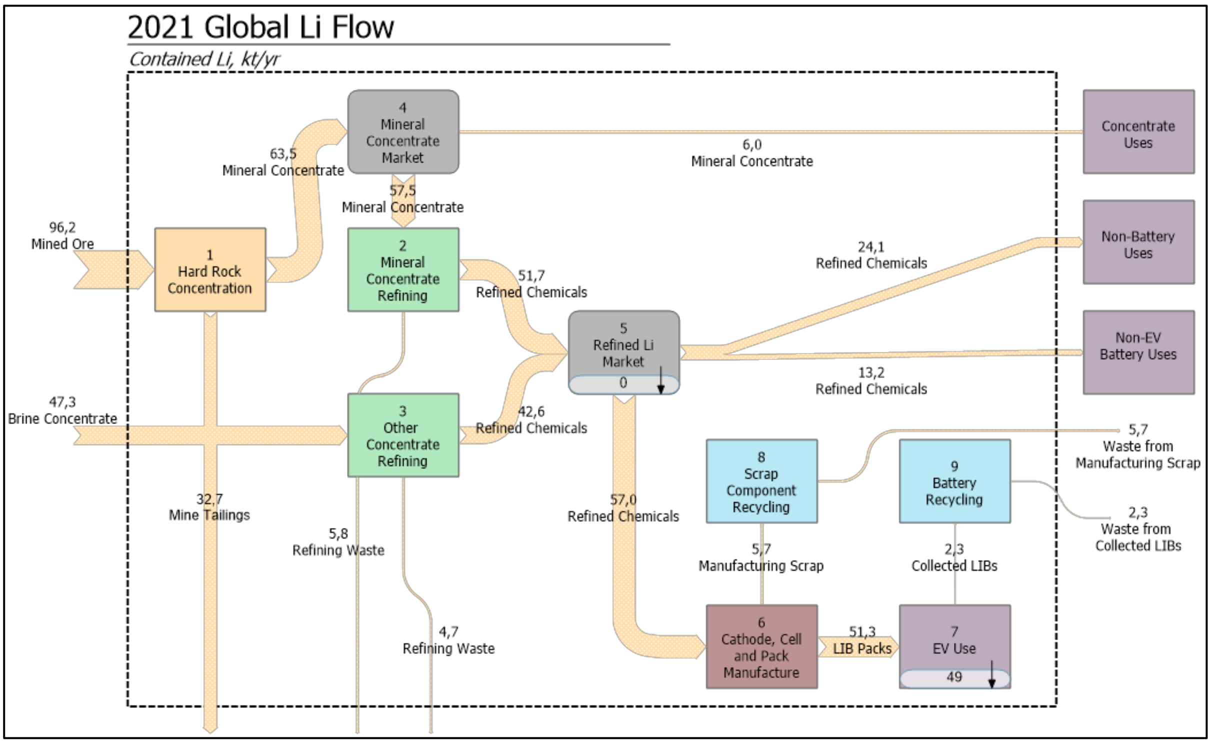

Figure 7: 2021 Global Lithium Flow. Supply and demand are balanced about the two market processes.

The quantification shows that both brine and hard rock sources contributed significantly to overall supply. There is notable Li consumption for uses outside of the EV sector. Despite this, the greatest market demand comes from LIB manufacturing for EVs. Li lost to mine tailings from the concentration of hard rock ores is significant, as are Li volumes in refining waste. While a small amount of Li wastes originated from EOL EVs, more than double this amount exited the system as waste in the form of manufacturing scrap.

3.2 Supply Scenarios

The three-tiered scenario construction for each of the ten groupings resulted in a total of thirty supply values. A wedged display of the different supply scenarios is shown in Figure 8.

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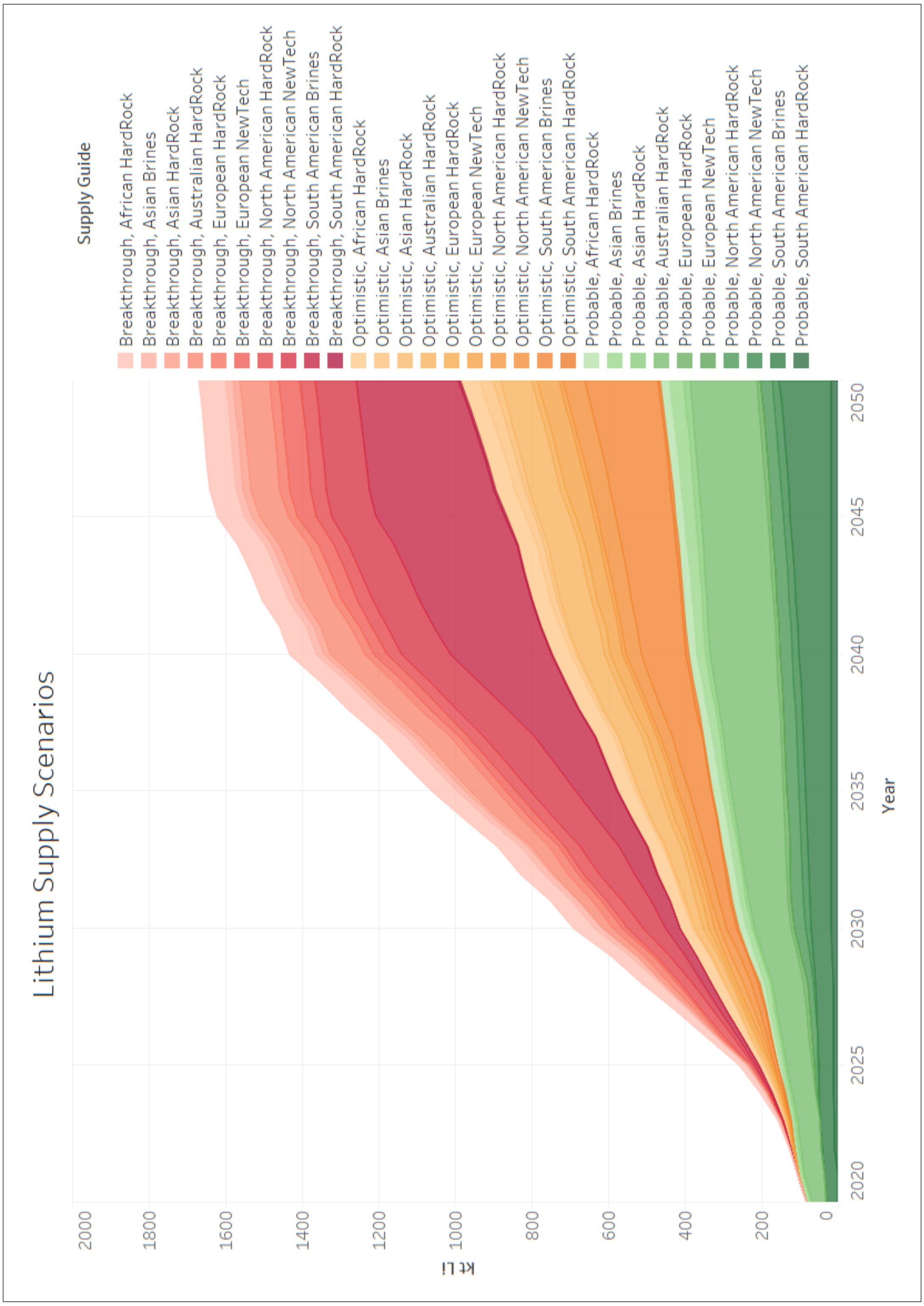

Figure 8: Supply Scenarios. Green, Orange and Red wedges represent probable, optimistic and breakthrough supply levels, respectively.

The display of the supply wedges is not intended to be interpreted with any set hierarchy, other than the supply levels in each individual grouping. Breakthrough supply levels could occur in some regions before optimistic supply levels occur in others.

The scenarios show that there is a very large variation between the potential future supply possibilities of Li. Most of the groupings show substantial increases as they move from probably to optimistic supply levels, and then from optimistic to breakthrough supply levels. The breakthrough supply levels from South American Brines make up the largest supply contribution of any single wedge by the end of the model, not surprising considering the encompass the three country with the largest Li resources (Argentina, Bolivia and Chile).

The variations continue to diverge over time as uncertainty behind the data and assumptions increases. Though ten groupings were given equal consideration for this analysis, the results show that there are some regions with much greater importance than others. Australian Hard Rock and South American Brines are the greater producers at all scenario levels. Other groupings, such as South American Hard Rock, look to be relatively small contributors.

These supply scenarios also resulted in varying amounts of Li losses, both in the form of refining waste and mine tailings (Table 8). By 2050, cumulative wastes from either of these sources under optimistic or breakthrough conditions are higher than any scenario of 2050 supply. Cumulative Li in mine tailings under the probable scenario was over double that of maximum modelled supply in 2050.

Table 8: Cumulative wastes from the Li supply system from 2020-2050. Values represent the range from all regions at probable supply levels to all regions at breakthrough supply levels.

Supply Scenario (All Regions)	***Li to Refining Waste (Cumulative kt 2020-2050)***	***Li to Mine Tailings (Cumulative kt 2020-2050)***
Probable	3505	1225
Optimistic	5421	2355
Breakthrough	8316	4358

It should be noted that these wastes do not consider wastes from the system before 2020, as well as unexploited Li in mine tailings from mining of other metals such as tin and tantalum.

3.3 Demand Scenarios

The MATILDA model was run for the 9 specified scenario combinations. The output of this was then used to quantify total primary demand for each year. The total primary Li demand for each scenario is overlayed for comparison on top of the supply scenario results (Figure 9).

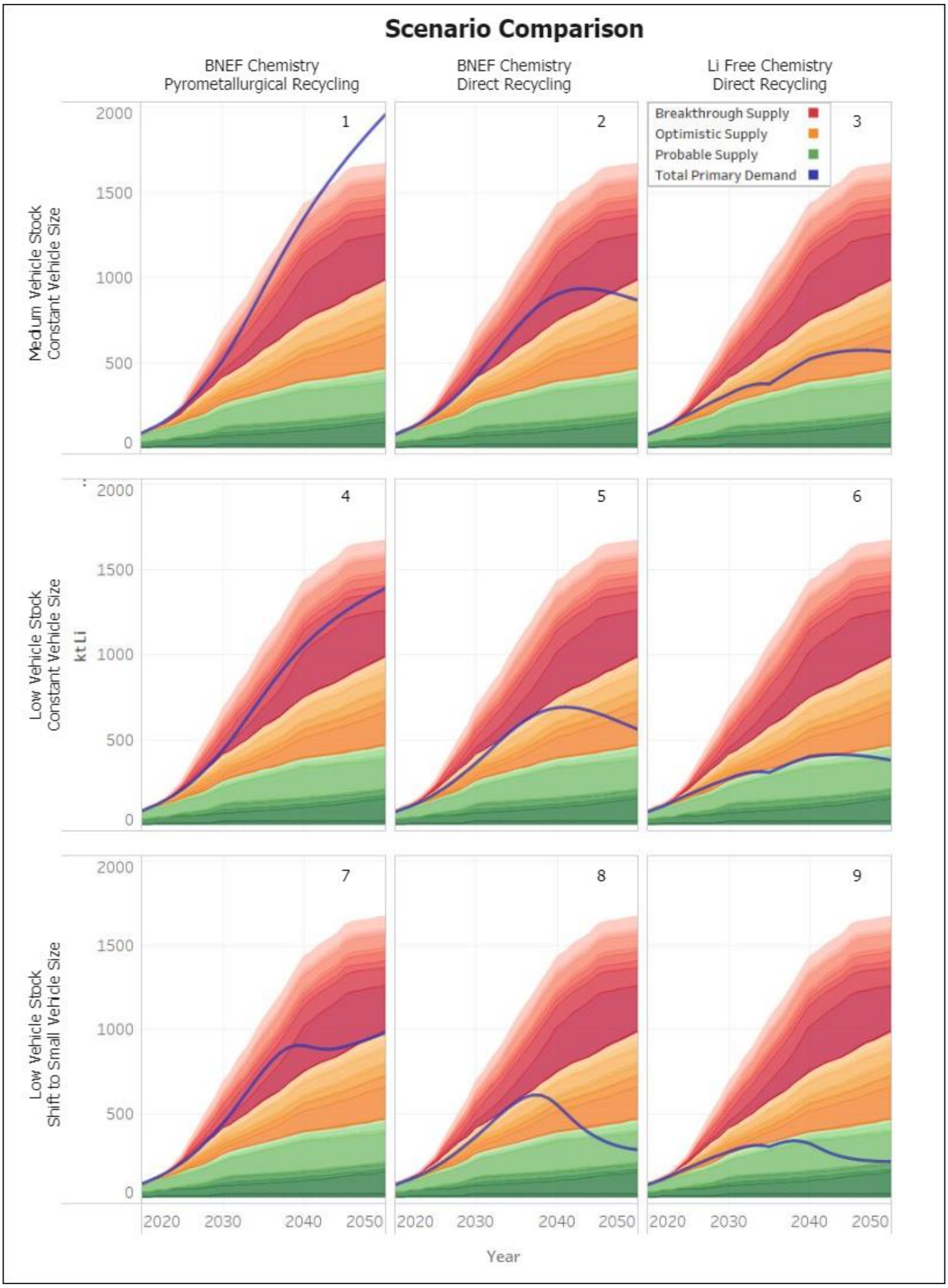

Figure 9: Demand Scenario Results. Total primary demand is compared against supply at probable, optimistic and breakthrough levels. Changing position on the x axis leads to a scenario with different technological interventions. Changing position on the y-axis leads to a scenario with different societal interventions.

Overall, the total demand varied greatly depending on the different interventions chosen, in both societal and technological directions. Scenario 1 (Figure 9-1), the closest concept to a "business as usual" situation, quickly relies on supply to reach breakthrough levels in multiple regions, as well as optimistic levels in all regions. It should be noted that the reliability of the results decreases significantly over time. Scenario 1 shows that no supply can meet this demand through the 2040s, but this is of considerably less concern than the high levels of breakthrough supply required in the 2020s and 2030s.

The technological measures modelled here are by no means trivial in nature, but yield significant results nonetheless. By moving to Scenario 2 (Figure 9-2), which applies a 90% direct recycling rate to all batteries from EOL LIBs and all manufacturing scrap, demand is reduced considerably in the long term. Despite these reductions, optimistic supply from all regions and breakthrough supply from some others is still required. More notable is that demand is only reduced marginally in the near term, with optimistic supply levels from all regions required up until 2030. Moving to Scenario 3 (Figure 9-3) significantly reduces demand in both the short and long term, keeping demand to within optimistic supply levels. Despite a rapid shift away from LIBs beginning in 2025, Li demand continues to grow. However, this growth occurs at a much slower and potentially more manageable rate.

Social measures also yield significant gains. Lowering the vehicle stock in Scenario 4 (Figure 9-4) has a similar effect as recycling in the short term, although in the long term a significant amount of breakthrough supply is still required. Adding a reduction in vehicle and battery sizes in Scenario 7 (Figure 9-7) decreases demand to similar long-term levels as in Scenario 2. Without recycling of existing Li, demand continues to grow at the end of the model period.

The greatest reductions in demand are realized when societal and technological interventions are combined. Scenarios 5 (Figure 9-5), 6 (Figure 9-6) and 8 (Figure 9-8) all largely avoid reliance on breakthrough supply levels. However, by using all possible interventions, as is done in Scenario 9 (Figure 9-9), the system completely avoids breakthrough levels of supply. By the end of the model, demand is well below the interface between probable and optimistic supply.

However, this scenario, which takes on significant and deep interventions, still requires approximately two and a half times the mined supply in 2030 compared to 2021. Although Scenario 9 generally only relies on probable supply for most of the model duration, in the early years considerable input from optimistic sources is still required. This demonstrates that none of the interventions modelled here have a significant impact on reducing a potential supply-demand gap in the short term.

4 Discussion and Recommendations

4.1 Limitations and Value of the Work

4.1.1 A Comprehensive Scenario Analysis

This study attempts to construct quantitative scenarios based on a wide and diverse amount of information from both qualitative and quantitative sources. The data collection and scenario construction were performed in a relatively short time frame without the aid of any quantitative modelling methodology (i.e. price, reserve modelling). While previous works may have focused on any combination of geologic or economic factors, this study adds value in that it considers the broader practical requirements of increasing supply. The wide range of possibilities between the different supply scenarios demonstrates the crucial role that social licensing, environmental inputs and technology could play in supplying Li for the energy transition.

An analysis such as this could benefit from two key developments. First, the availability of a more holistic and complete resource classification would be useful, such as one modelled after the UNFC [51]. While this might not explicitly determine the likelihood of future Li resources to be developed, it would provide a more solid starting point from which to construct future scenarios. It could also provide valuable information regarding the challenges with each specific resource and what mitigation options could be taken to address these challenges. This study relied heavily on market studies and company-published data. These studies provide valuable information but reducing reliance on works such as these that contain a large inherent bias is desirable.

Second, a structured framework that uses the key inputs described here could be developed. This would ideally create a more systematic way to take the concerns present and to output future likelihood of supply. Such a framework would possibly require the use of a unique combination of quantitative and qualitative methodology, such as has been explored before for conflictive environmental issues [57]. By having a resource-development specific methodology such as this available, along with structured resource data in line with UNFC requirements, criticality could be assessed for metals and minerals in a relatively rapid and robust manner.

The results show that there is a significant risk of Li shortages in the very near term. Because of this, all efforts to conduct further research and improve available data should be done with an understanding that concrete actions are also urgently required. The Li system is rapidly evolving and research in this area should attempt to keep pace with these developments.

4.1.2 Supply, Demand and Stocks

This model attempts to model supply and demand independently in order to understand what steps should be taken to avoid large discrepancies between the two. It should be reinforced that the supply and demand systems are absolutely not independent of one another in reality. An excess or shortage of supply could affect prices, investment, or production plans. Furthermore, a shortage of supply with system needs that are still growing on the demand side could mean that challenges in bringing new supply online could only continue to build as time goes on.

The methodology used here assumes that Li is extracted, processed, refined and sent to end-uses within one-year boundaries. This is not an accurate representation of reality since many processes within the system are time intensive and could span multiple years. Each process within the life cycle of Li could also occur in different years – vehicles are often sold using Li that was extracted in the previous year or two. This means that, in a growing system, demand in one year often requires greater supply in the previous years than is projected in this model.

The methodology also does not account for buildups of Li stocks. These stocks could accumulate in either of the market processes (Process 4 and/or Process 5). Stockpiling at this stage has potentially occurred in large amounts in the past [39]. While storing large quantities of mineral concentrate for extended durations is feasible, a key assumption here is that Li chemicals do not have a sufficient lifetime to be stockpiled at a large scale.

To explore the possible outcomes of these assumptions being incorrect, an analysis was run that aimed to understand if built-up stocks of Li could have a significant impact on contributing to supply within the system. This analysis ran all possible combinations of all supply scenarios (59 049 total combinations) with selected demand scenarios and output how many supply combinations could fulfill demand in each year if stocks were held over and used from previous years. It was found that, for the key scenarios chosen, considering stocks did not have a sfurther in section 7 of the supplementary information.

4.2 End-Uses and Strategies to Reduce Demand

4.2.1 Personal Transport Policies

The scenarios explored here shifted between medium and low vehicle stocks, as well as between constant and reduced battery sizes. Under no scenario with a medium vehicle stock and a constant battery size did demand ever fall into the probable supply range or completely avoid breakthrough levels. Whether with or without technological interventions, these societal interventions were successful at bringing demand to within a more reasonable range of Li supply.

Reducing vehicle ownership rates, and therefore the overall vehicle stock, is a complex issue that will not be exhaustively addressed here. However, it must be recognized that doing this requires vast transformations, both within the transport and other (such as housing) systems. As policy makers consider how to best shift from ICE to BEV drivetrains, adequate consideration should simultaneously be given to the improvement of these adjacent systems.

A reduction in battery size requires either smaller vehicles and/or vehicles that have a shorter single-charge range. This is also a difficult area to address – one of the main concerns regarding EV ownership in the early years has been the inability of EVs to replicate the range of vehicles with ICE drivetrains. Reducing battery size could push consumers back in the ICE direction. However, taking steps such as significantly building out charging infrastructure and, again, deep changes in transport and non-transport systems could help alleviate some of these fears while also reducing the required battery size. In 2012, Mohr & Mudd predicted much lower lithium production and consumption [31]. However, they also assumed an average battery capacity of 20 kwh, or 3 kg of lithium per electric vehicle, much lower than any values used here. This shows how much technology and battery costs have shifted since then. If technological improvements in LIBs reach their limits and material costs begin to have an outsized impact on vehicle price, a reverse in the trend to larger battery capacities could occur. If EV costs become significantly influenced by battery costs, a reduction in battery sizes could help make EVs more accessible to a wider range of consumers.

Because of the observed difficulty of the Li supply system to meet demand under medium vehicle stock and constant battery size conditions, MATILDA scenarios which explored a high vehicle stock or an increase in average battery size were not explored. However, there is still a distinct possibility that the compass of society might move in this direction. There are two main reasons behind this. First, one could argue that the shift from ICE to BEV drivetrains has, to this point, occurred mainly in smaller vehicles or vehicles that are only required for lower-range applications. As the EV system expands to include a greater diversity of vehicles, demand for larger batteries in larger vehicles could grow. Second, there may not be global political or personal will to keep vehicle ownership rates at or below those used in the medium vehicle stock. Regions of the world with large populations and low (but growing) vehicle ownership rates, notably in large African and Asian countries, could see an increase in their vehicle stock at a greater rate than expected. If this is not offset by an equivalent reduction from more static vehicle systems in Europe and North America, demand for Li due to increased vehicle ownership could potentially quickly jump beyond breakthrough Li supply levels.

Finally, while significant, the reductions in demand modelled here due to a reduced vehicle stock and/or average battery size were not so significant that they considerably alleviated supply concerns. Without technological interventions, societal interventions alone required breakthrough supply from multiple regions for the entire duration of the model. This means that if these technological interventions fail to occur at the required scale, the social interventions explored in this study might be inadequate.

The technological interventions enacted here may have a much stronger effect than societal interventions due in part to the fact that the ambitiousness of the former is much greater than that of the latter. It is strongly recommended that there is a sincere examination of how society could reduce vehicle ownership and change our relationship with personal vehicles at a much deeper level than is considered here.

4.2.2 New Battery Technologies

One of the most concrete recommendations of this study pertains to battery composition. The results clearly show that rapidly implementing a greater share of non-Li chemistries can help keep within predictable and reliable supply, without reliance on breakthrough technologies or undue social licensing. If we move forward with a vehicle system that is completely reliant on LIB chemistries, this system may in turn become reliant on breakthrough supply levels.

This is not to say that supply issues with materials used in non-Li battery chemistries will be benign. But by diversifying the portfolio of technologies (and the required material inputs for those technologies), there is a great reduction in exposure to the risks associated with shortfalls or issues with any one particular material. Similar to how LIB battery chemistries have attempted to phase out cobalt as much as possible, there needs to be a sincere attempt to bring non-Li batteries to market as soon as possible. This has been argued by researchers previously [58],[59]. Some larger players [60] and smaller upstart companies [61] have also recognize the opportunity associated with non-Li batteries. Such efforts should be supported and accelerated with similar urgency and attention currently being given to LIBs and their associated supply chain development.

Furthermore, it is also recommended that the technological approach to the energy transition in general is altered. Instead of designing and implementing technologies with the assumption that supply of materials will always be unlimited and market forces will make the required supply available, the design process needs to consider material abundances and the ability to use these materials at scale. There also needs to be a recognition that this approach might lead to technologies with lower performance (i.e. lower energy density in batteries without Li) but that these trade offs are necessary.

4.2.3 Heavy Duty and Stationary Storage

This study does not consider LIB use in any larger form of transport. That being said, LIBs have made their way into other aspects of the transport system, including in busses, ferries [62]–[64], commercial trucking [65], mining equipment [66] and even trains [67]. These vehicles, naturally, use batteries that are much larger and contain much more Li. The usage of batteries in these areas could have large benefits, perhaps in some cases larger than personal EVs – the capacity might be more efficiently used in public transport or industrial applications. However, once again, the use of different battery chemistries (or other technologies, such as hydrogen) needs to be explored, especially for vehicles where energy density is not of great concern. Additionally, many of these areas could attempt to take advantage of centralized energy distribution rather than energy storage (for example, tramways instead of electric busses, trolley-assist mining equipment and electrified rail).

This study also does not consider anything more than minor growth in stationary energy storage using LIBs. One of the main advantages of LIBs is their high energy density. Although this is a key issue when looking for technologies that can power personal vehicles, energy density does not warrant the same level of concern when being considered for stationary storage applications. Energy storage is not exclusively a battery field, of course, but where batteries are determined to be desirable it is once again recommended that alternative chemistries be explored. The IEA has recommended and modelled vanadium flow battery use [53] while sodium and zinc ion batteries [68] have also been explored for stationary use. The results demonstrate that the Li system does not need this extra and potentially large strain when other, more use-appropriate technologies could possibly be used instead.

4.2.4 Recycling

Based on both the difficulties of recycling Li and the large emphasis that has been placed on recycled material as a future resource, it is difficult to say how much Li exactly will be recovered by future processes. Pyrometallurgical, hydrometallurgical and direct recycling methods all provide different recovery rates, with large variations within the latter two processes [13]. There was no attempt made in this to take a “middle ground” approach. Rather, the direct recycling parameter chosen reflects absolute best-case conditions for the system. The modelling results show that, although recycling alone is not enough to alleviate supply concerns, development of recycling systems at high overall recovery rates is one of the best long-term strategies to reduce primary supply. Significantly more waste came from manufacturing scrap in 2021 than from EOL LIBs. This is the area where immediate action is required, while continued strong investment into development of recycling systems and technology is needed to have a strong effect in the long term.

The results show that LIB recycling will be required just to fulfil the demand requirements of the system. However, high recovery rates of recycled Li, along with other successful interventions in production or end use of Li, could result in a peak for Li demand. Careful thought must be given to the desired outcome if this is to happen. There are many benefits to using recycled material as a feedstock, but new Li technologies could make primary extraction potentially more economic (as it has been in the past) and less energy intensive. If it is deemed desirable from a societal perspective for recycled material to be used over extracted material, policies need to be put in place to encourage recycling over potentially cheaper alternatives.

4.2.5 Other Li Uses

With so much attention being given to batteries, it should not be forgotten that there are other important and historical uses of Li. A potential scarcity could drive up costs, bringing about either higher prices for consumers of these end use products or the need for substitutions. Figure 1 provides a useful starting point from which one can understand what industries could potentially be affected, including pharmacy, casting and production of glasses and ceramics. In contrast to this concern, it should also be recognized that not all feedstocks, concentrates and refined chemicals are suitable for battery production. As the Li system scales up, there could be an excess of availability of these non-battery grade products.

4.3 Resources and Primary Production

4.3.1 Environmental and Social Concerns: More than just morality

There is a large obligation by all stakeholders involved in extractive projects to undergo proper due process with respect to environmental and social performance. However, aside from this strong moral imperative, there needs to be an increased understanding that these are actually key inputs and requirements for the success of resource development projects. This could likely increase in importance if a rise in world population is compounded with serious environmental degradation and greater social volatility.

A very large range in the supply scenarios can largely be attributed to uncertainty regarding whether social licensing and the necessary environmental requirements can be obtained for projects in a timely manner. Furthermore, much of the potential of breakthrough technologies such as DLE is heavily dependent on the appropriate water requirements of these technologies.

The results also show that, under all demand scenarios, large individual projects or expansions do not have a significant impact on easing overall global supply concerns. This means that there needs to be a larger and more systematic effort amongst industry and governments to consider the environmental limitations of the areas they operate in, as well as the wishes and concerns of civil society and indigenous groups. The largest resulting variation in supply between the three scenario levels occurs in the South America Brines grouping. If the highest levels are to be achieved here, coordinated strategies regarding water use and social licensing agreements will have to be put in place. Improvements in social licensing at one location or for one large project will do very little in the big picture if these are not shared in the greater area.

The results also show that supply could struggle to meet demand for the entire duration of this model. If that is the case, social and environmental considerations can not be adequately addressed through short-term or band-aid solutions. Until steps are taken to reduce overall Li demand, or to at least reduce the rate at which it is growing, long-term and meaningful solutions are needed to alleviate the concerns of the stakeholders affected by extractive projects. The way in which the extractives space interacts with society needs to be addressed through, once again, a coordinated effort between industry, governments and civil society.

It should also be noted that many projects here could be affected by environmental or social limitations posed by non-Li resource extraction. Social opposition and environmental impacts are by no means exclusive to Li projects. The ability of Li extraction to exist within this larger system in a symbiotic way is crucial to the success of future metals production.

This study highlights many of the flaws that are present in the extractives system that is the backbone of the energy transition. Similar to how it is recommended that there is a sincere examination of society's relationship with the personal vehicle, it is also strongly recommended that the ways in which society relies upon and interacts with the extraction of raw materials is thought of in a way more suitable for our long-term future. This may have to go deeper than just technological improvements or due consideration being given to environmental and social concerns.

4.3.2 New Li Technologies and New Resource Types

The results show that significant interventions are required to bring demand down to a level not requiring breakthrough supply. Because of the complex nature of these interventions, there is a good chance that they could only be partly successful. Even in combination with meaningful progress regarding social measures and environmental management, extraction using existing technologies may not be enough.

There are several new technologies that are being explored as potential solutions to increasing supply. DLE is often seen as a potential game changer, with the possibility to provide low carbon, low footprint extraction of geothermal and oilfield brines in the subsurface [69]. In addition to this, the potential to apply DLE to extraction of continental brines could the lower costs and the visible environmental footprints generally associated with these operations. Extraction from clays and other volcano-sedimentary sources, such as jadarite, is a part of planned projects this decade. Extraction and processing of petalite and lepidolite ores, historically not suitable for eventual battery use, could see technological breakthroughs to make processing and refining to battery grade material possible.

However, with the exception of DLE methods enhancing evaporation at continental brine sites, there are no known producing operations that use any of the technologies listed above. The ability of the system to expand at breakthrough levels is largely tied to the use of new and innovative technologies. While all efforts should be made to encourage these technological developments, caution should be used when relying upon new methods that have not been proven at scale. Even if successful, there is a good chance that the ability of these methods to provide supply at the promised levels has been overstated. It is recommended that new technologies are not used as solutions for policy makers to address the issue of a potential Li supply shortage.

The increased monetary and environmental cost of extraction as ore grades and resource qualities decline has been of growing concern [6], [70]. While Li has not been extracted and depleted at nearly the scale as copper, for example, there is still the risk of similar concerns presenting themselves here as time goes on. In recent years Li has largely been extracted from good quality, high concentration brines in South America, where energy inputs have been relatively low. As the system expands to include brines of lower concentrations and with higher magnesium contents, the overall costs of extraction could rise significantly. The same can be said about Li from hard rock sources. Greenbushes in Australia has been the largest producer of Li mineral concentrates in recent years [53]. This is an exceptionally high quality deposit, with a high Li grade, large size and easy access due to little overburden material [15]. Again, as the system expands, the average Li ore extracted will likely not be of this quality [53].

If the case, this will result in an increase in the “Rock to Metal Ratio (RMR)”, or the amount of disturbed material that is required per produced unit of end-use metal. Because of the increased requirements to extract lower quality resources in this potential reality, new extraction and processing techniques should be developed to keep the monetary and environmental costs within a reasonable range. It is recommended that existing, proven methods of Li extraction and processing are examined and improved upon as much as possible. If this is not possible, it must be accepted that the environmental performance pertaining to water and energy use concluded by previous studies [45], [46] may decrease.

Harvesting Li from mine and process wastes is another strategy that could have potential moving forward. Extraction from these waste areas could be cost and energy intensive, with lower grade and poorer quality material, but roadblocks to approval could be lower due to the lower additional disturbance of this type of extraction. Social licensing could also be more straightforward and more easily obtained in a genuine manner. This could require government incentives and support, something which is already happening for the exploitation from metals in general in some jurisdictions [71]. The supply scenarios all produced very large amounts of cumulative Li as a part of waste flows in the form of mine tailings and refining waste. Even if these wastes are not economic for further processing when they are disposed of, disposal and storage methods should keep potential future exploitation in mind. This can be done through strategic construction and planning of tailings disposal areas [72]. In addition, because Li is often geologically found alongside tin and tantalum [4], legacy waste dumps at extraction areas that formerly exploited these metals can be looked at as a potential resource.

Geological exploration and future discoveries were not greatly considered as a part of this study. Although new discoveries of Li could be important for future supply, because of the large time required to bring a new deposit into production, it is not thought that any new discovery could have a great impact on this study's overall findings. This does not mean that new discoveries could not contribute in the future, but rather that there are short and long term concerns visible now that must be solved through other avenues.

5 Conclusion

This thesis used dynamic material flow analysis methodology to compare different possibilities of future Li system conditions. The MATILDA model was used to construct appropriate scenarios of Li demand from electric vehicles. A holistic assessment of Li resources was performed to construct scenarios of Li supply at probable, optimistic and breakthrough confidence levels. These different scenarios of supply and demand were compared to understand under what conditions the system could face a shortage of Li and how interventions in the system could effectively mitigate this risk.

The results of the work demonstrate that there is a significant possibility of Li demand outstripping supply in both the short term and throughout the duration of the study period. Goals to substantially increase supply are largely dependent on the adoption of widespread and effective social and environmental measures, with coordinated support between governments, industry and civil society. In addition, extraction technologies that are not currently feasible from a techno-economic standpoint today may be needed to avoid a potential future gap.

Interventions to reduce demand from both a technological and societal standpoint were found to be successful. Meaningful demand reductions were only made when multiple interventions were combined with one another. Technological interventions were found to be more effective than societal interventions in the short term, while societal interventions had a larger impact in the longer term. The societal interventions explored here may have had a lower impact because of their smaller scale in comparison to the ambitious technological changes proposed regarding recycling and battery chemistry shifts. Even when all interventions were implemented, there was still a need for significant growth in Li supply by 2035.

It is recommended that, to mitigate this risk of a supply shortfall, all reasonable steps be taken to reduce demand. There is a need for the development of robust collection and recycling systems for both battery manufacturing scrap and EOL batteries. A materials-considerate approach is needed for the development of scalable, non-Li battery technologies. All reasonable measures should be taken to reduce the need for personal vehicles in general, as well as the need for large vehicles with long single-charge ranges. Significant and immediate investment is required to improve the technological, environmental and social performance of the Li extractives system.

Moving from probable to optimistic and finally to breakthrough supply levels could increase exposure to unreasonable social and environmental consequences as a result of Li extraction. As a society we should be seeking to decrease our exposure to these risks. While the world attempts to transition to a decarbonized transport system, further work needs to be done to understand how deep changes can be made to society's reliance on personal vehicles. Additionally, as metals such as Li see unavoidable and large increases in primary demand, a comprehensive rethink of society's continuation with our extraction-based socioeconomic paradigm is strongly recommended.

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Appendix A: Supplementary Information

Supplementary Information for "The Complex Nature of Lithium Extraction – A dynamic material flow analysis to understand supply constraints in the transition to electrified transport"

Brent McNeil

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1 MATILDA Model Methodology

Vehicle Stock

The stock of *all* in-use *passenger* vehicles is driven by population and the number of vehicles per-capita globally. Population data is taken from the United Nations, while per-capita vehicle regions is broken down by region. Based on past data and chosen future targets, each region is assigned a logistic regression for ownership levels at low, medium and high levels.

This produces three potential levels of global vehicle stock (Figure 1).

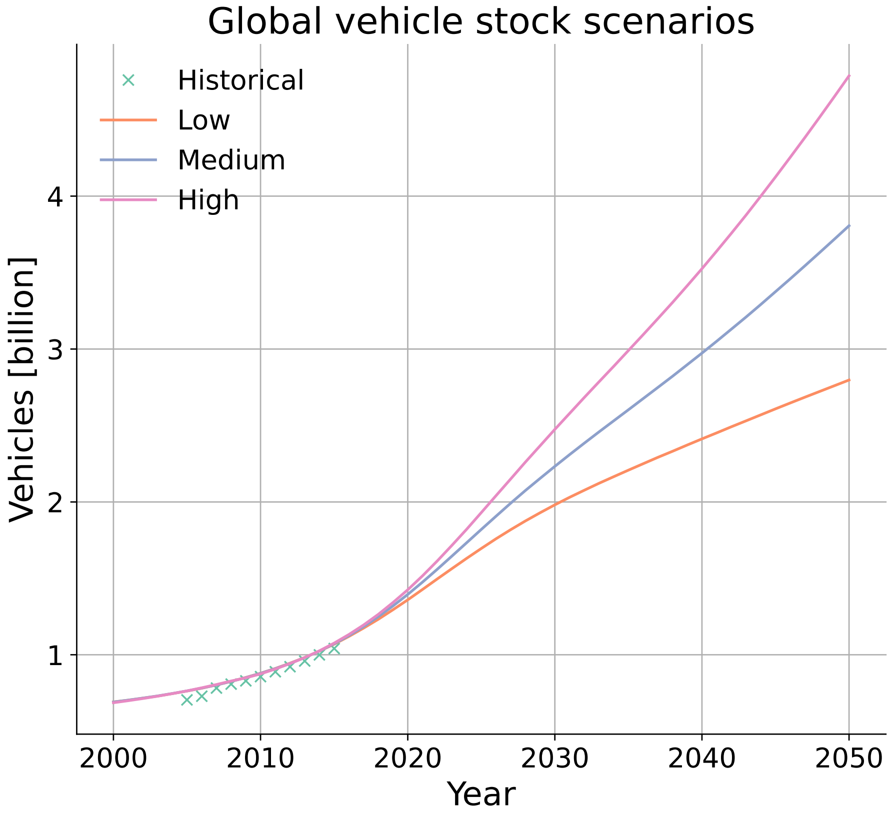

Figure 1: MATILDA vehicle stock scenarios

In this model, the high vehicle stock scenario is not considered. This is based on the assumption that while efforts to *limit* global ownership of vehicles may fail, accelerating the pace of vehicle ownership more so than in the medium and low scenarios is not plausible. It should be noted that both the medium and low scenarios still assume large growth in vehicle ownership. The only region in which per capita ownership of vehicles declines under any scenario-region combination is in the US and Canada .

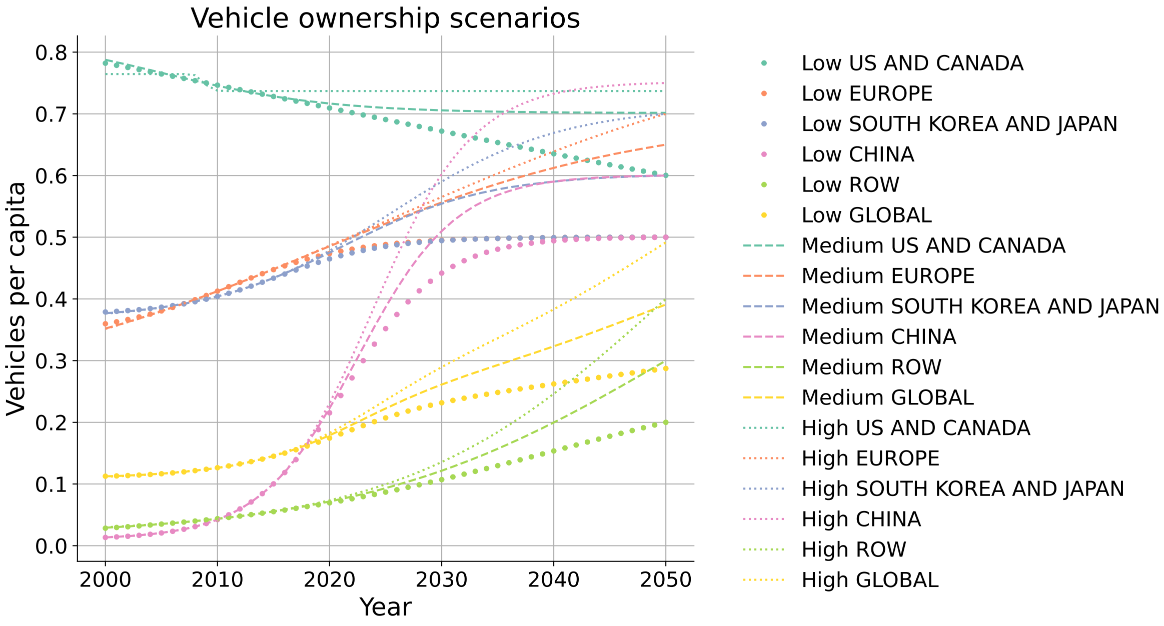

Figure 2: MATILDA vehicle ownership scenarios

EV Penetration

The vehicle model uses values derived from the scenarios in the World Energy Model (WEM) from the International Energy Agency (IEA). Three scenarios are included as modelling options: Net Zero Emissions by 2050 Scenario (NZE), Sustainable Development Scenario (SDS) and Stated Policies Scenario (STEPS). Based on these scenarios, values for BEV and PHEV penetration were calculated (Figures 3 and 4). NZE is the most ambitious of the scenarios, with SDS offering an ambitious but more conservative pathway and STEPS relying on stated policies from nations while being the least ambitious. For the purposes of this analysis, only the SDS was considered. This choice is based on the assumption and observation that personal transport sector may be one of the few areas of the energy transition where consumer attitudes are accepting of electrification and where consumer demand may indeed outpace overall country targets. This means that any work using STEPS values likely underestimates the future trend. A preliminary analysis of demand from NZE very quickly concluded that Li demand from this scenario was untenable and not worth exploring with the current supply situation.

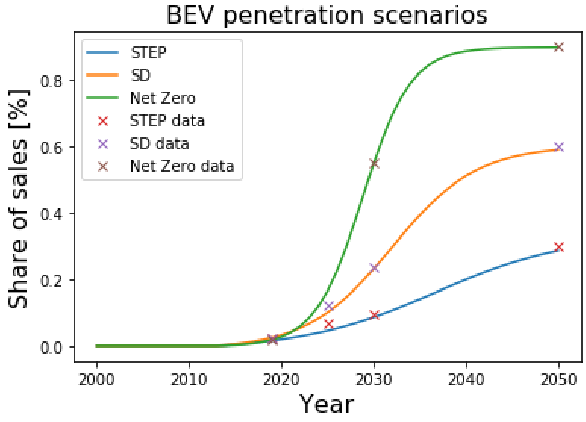

Figure 3: MATILDA BEV penetration scenarios

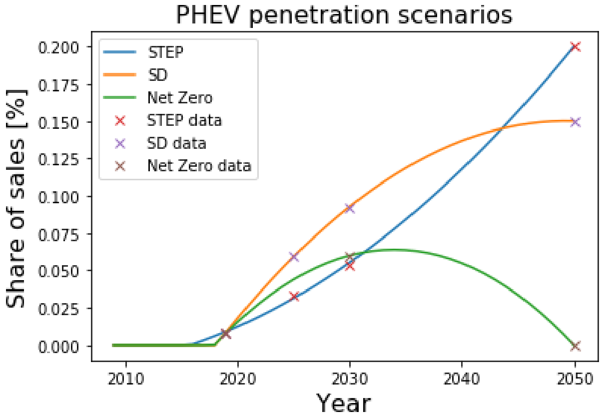

Figure 4: MATILDA PHEV penetration scenarios

The SDS is defined as a "well below 2 °C" pathway that puts the energy system on track to meet key sustainable development goals (SDGs). Advanced economies reach net zero emissions by 2050, with China and India following suit in 2060 and 2070, respectively.

Battery Chemistry

The vehicle model contains many different chemistries that are useful in displaying material requirements for many metals, such as nickel and phosphorus. For conventional LIB technologies, including Lithium Ferric Phosphate (LFP), Nickel Cobalt Manganese (NCM) and Nickel Cobalt Aluminium (NCA), the contained Li per unit of energy does not shift a significant amount. Shifting between scenarios has a marginal effect on the model output. Because of this, a baseline LIB chemistry share was chosen, and two new chemistry scenarios were designed on top of this. These two new scenarios focus less on LIB chemistry and more on the potential impact of new and disruptive technologies.

The baseline "BNEF" scenario is based on information from Bloomberg New Energy Finance (BNEF). This assumes that LIBs are the only battery technology in use throughout the model duration. There is a relative balance between NCA, LFP and various NCM technologies. The shares increase or decline at various rates before leveling out from 2030 onwards.

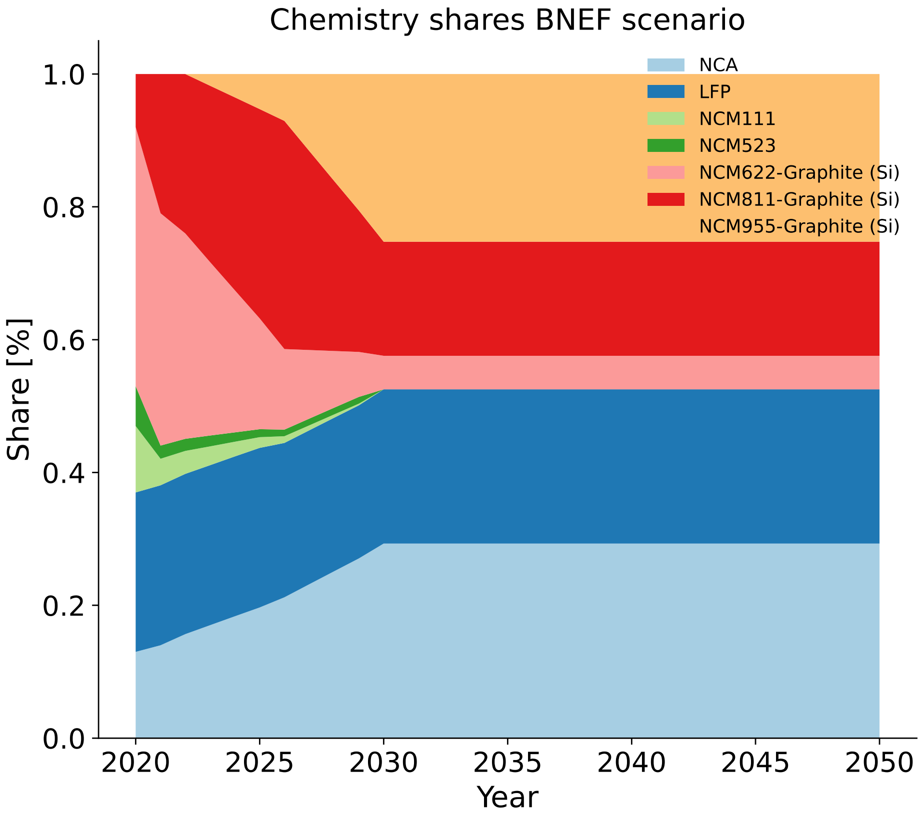

Figure 5: MATILDA BNEF chemistry share scenario

There is a, however, potential for innovative battery chemistries to disrupt the current LIB-dominance. These include technologies using Li-metal anodes and solid-state electrolytes. The advantages of these could include fast charging and much higher energy densities. For the second scenario of chemistry shares, the “Next Gen BNEF”, two of these technologies were included – Li-air and Li-sulphur. While Li-air and Li-sulphur batteries may not necessarily be the most promising future technologies, they still represent chemistries that have performance advantages and much higher contained Li than traditional LIB chemistries. These technologies are put into use beginning in 2030 and linearly take away market share from traditional LIBs until 2040, when they account for a combined 60% of vehicle sales. The remaining share of chemistries is distributed with the same ratio as in the standard BNEF scenario.

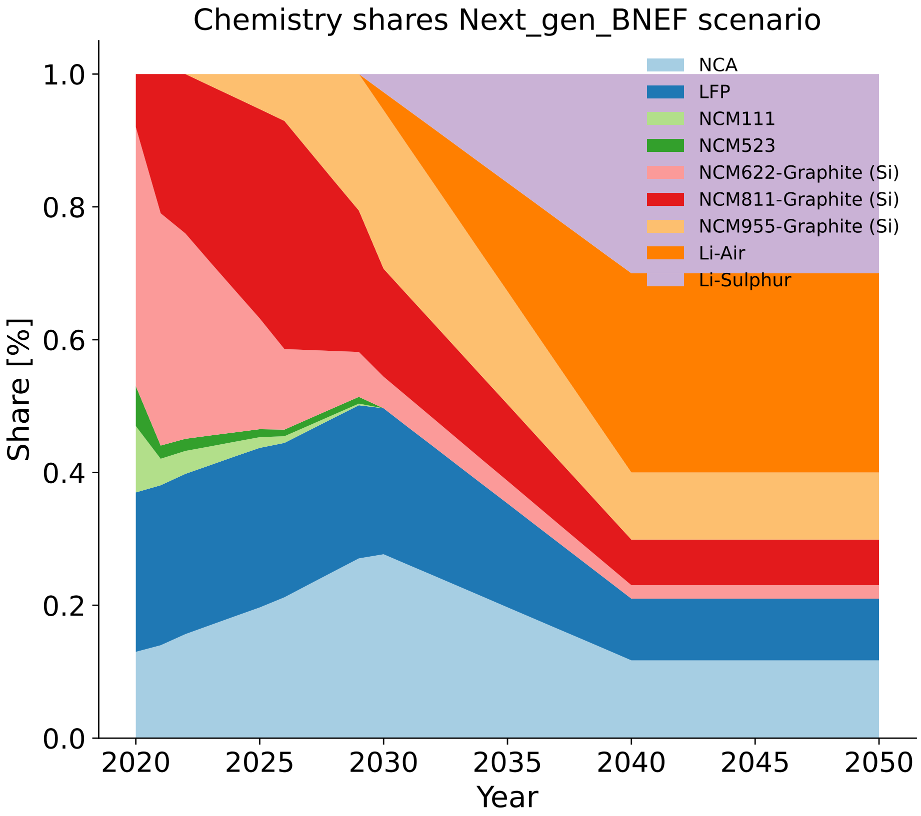

Figure 6: MATILDA Next Gen chemistry share scenario

The last chemistry share that was included in modelling aims to illustrate a vehicle market where battery technologies become prevalent that contain no Li at all. This could include, but is certainly not limited to, sodium ion (Na-ion), zinc ion (Zn-ion) and hydrogen technologies. Under this "Li-free" chemistry mix, Li-based tech slowly loses its total dominance to these technologies beginning in 2025 This continues at a constant rate until 2035, when 50% of all chemistries are Li-free. This chemistry share is meant to demonstrate a future with a greater diversification of technologies for different end-use applications: Li-metal batteries for ultra high-performance applications, Li-ion for proven and reliable use and lower-performance technologies appropriate for many every-day applications.

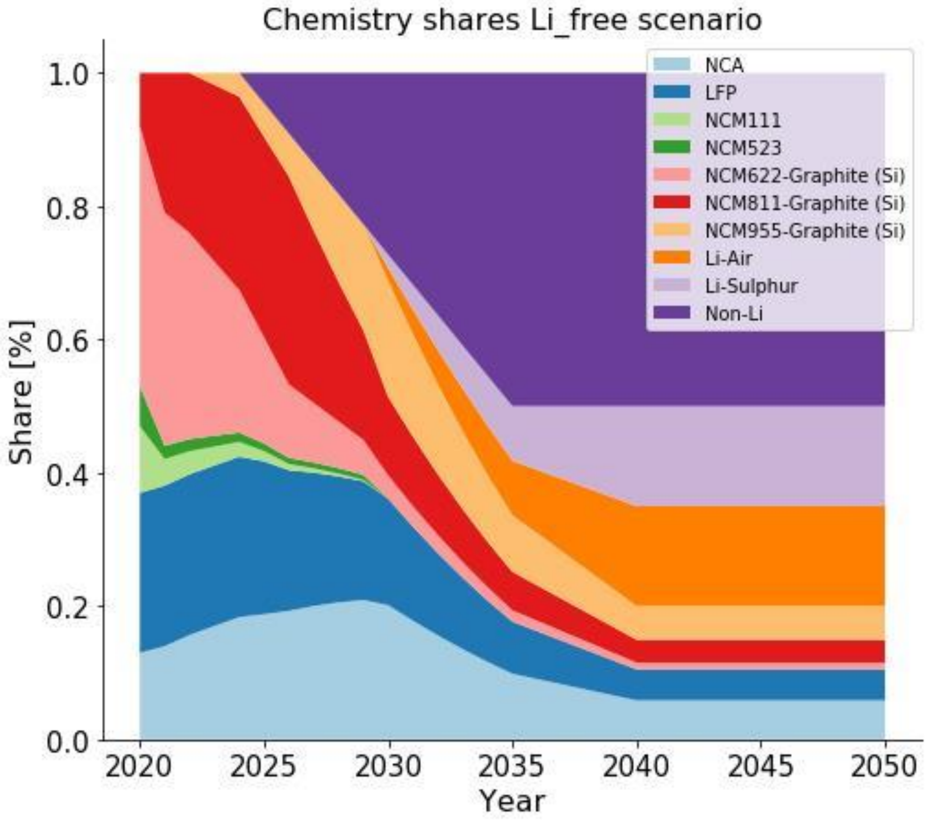

Figure 7: MATILDA Li Free chemistry share scenario

Vehicle Size and Battery Range

EVs require their mass to be propelled by energy stored in LIBs. Vehicles of larger mass require more of this stored energy to achieve the same distance travelled and vehicles of the same mass can travel further when a greater amount of stored energy is available. The amount of stored energy in an LIB is proportional to the required Li for that LIB. Therefore, vehicles with a greater mass or greater single-charge range require more contained Li.

EVs (and therefore LIBs) are defined by the model as coming in one of three sizes – small, medium or large. The share of these sizes over time can then be adjusted. The baseline “Constant” scenario (Figure 8) assumes no major future changes in the share of vehicle sizes compared to today. This assumes that charging infrastructure does not undergo major improvements and that consumer desire for larger and high-range vehicles persists.

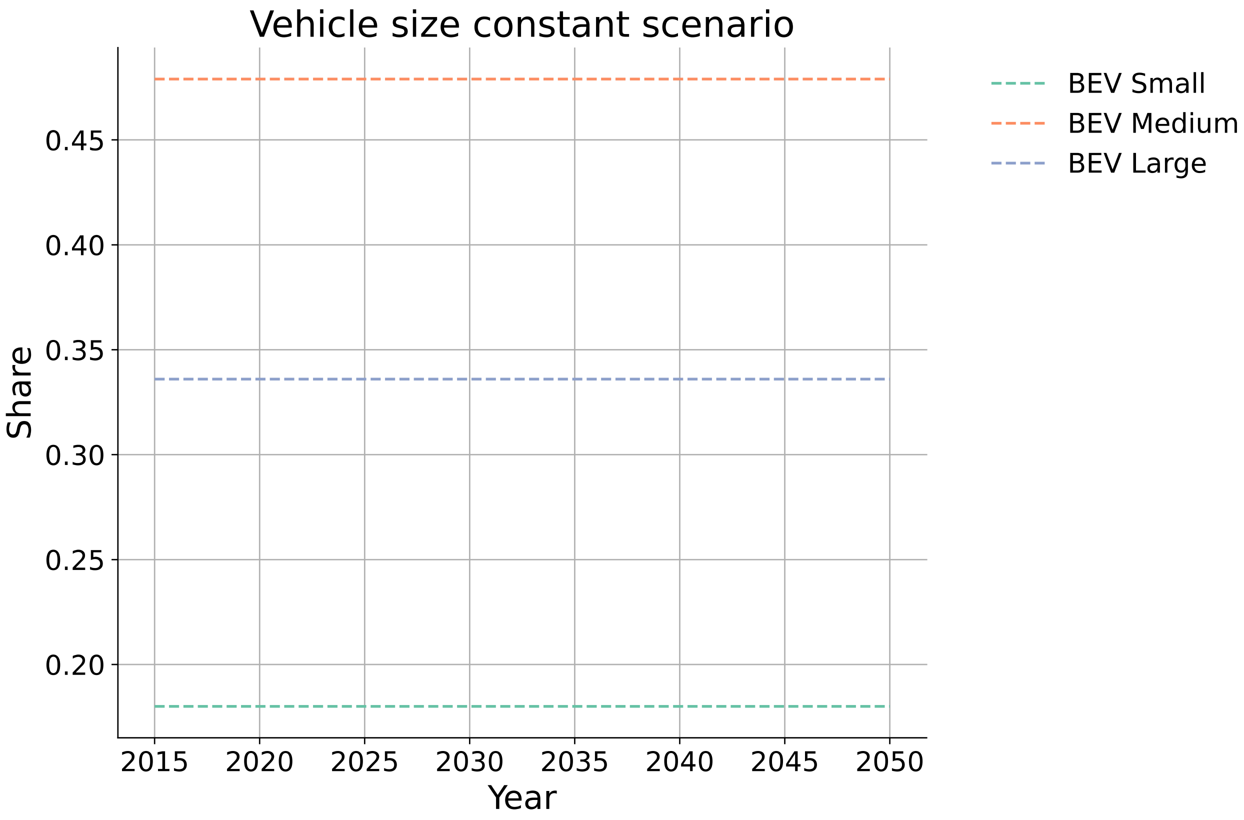

Figure 8: MATILDA constant vehicle size scenario

The “Shift to Small” scenario (Figure 9) assumes that because of some technological, societal or policy interventions, smaller vehicles and smaller batteries become much more common.

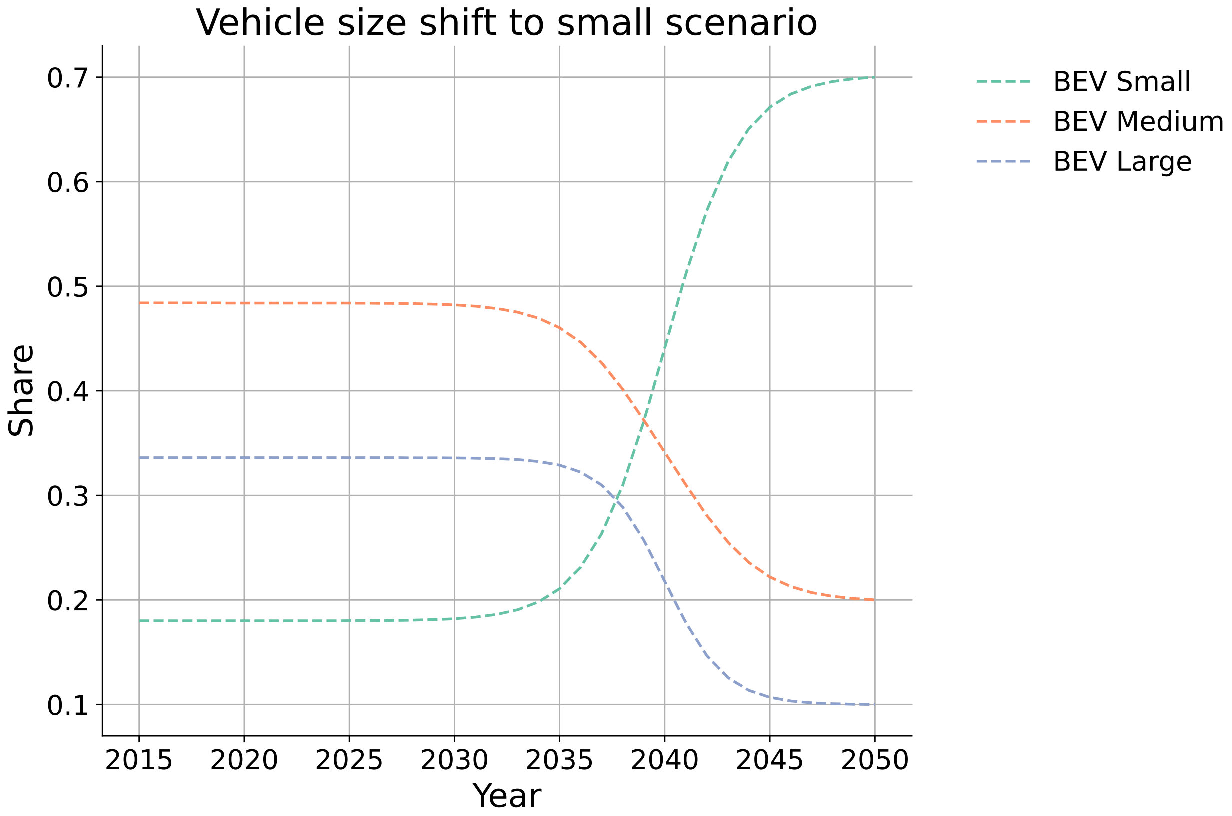

Figure 9: MATILDA shift to small vehicle size scenario

The “Shift to Large” scenario was not considered in the construction of overall demand scenarios. This assumes that affordability will prevent a larger share of large, high cost vehicles from making up an increasing share of the market as EV penetration trickles down into lower-cost segments with consumers from lower income brackets.

Recycling

The above parameters determine the total outflows of contained Li ($A_{7\text{-}9}$) from Process 7. At this point, the material enters the recycling process. Recycling methods of LIBS can essentially be classified into three different categories: pyrometallurgical, hydrometallurgical and direct recycling. The recycling process in this model only considers pyrometallurgical and direct recycling. Pyrometallurgical recycling assumes that no Li is recovered, with 90% recovery in direct recycling. While Hydrometallurgical options will be a key recycling technology moving forward and in the NTNU vehicle model is listed as recovering 40% of Li, this is not considered here.

2 Detailed Explanation of Required Inputs for the Lithium Supply System

The following is an exhaustive list of the inputs that are required for increased Li supply.

Geology

- The type of deposit and mineralization. Mineral resources include spodumene, petalite, lepidolite and jadarite. Brines can be characterized as continental brines, geothermal brines or oilfield brines. Sedimentary deposits can be found in the form of clays, jadarite or other rock deposits.
- The Li grade of mined ore in hard rock deposits, or the concentration of Li in brine or clays.
- Mineralogical characteristics of the ore such as hardness and liberation size during processing.
- The strip ratio at hard rock mine sites, or the ratio of waste rock removed to access the economic ore.
- Li resources and reserves as reported by the USGS.
- The concentration of various impurities in each resource, most notably iron in spodumene and magnesium in brines.

Environmental Requirements and Impacts

- Water requirements and depletion potential. Surface and groundwater are important for all extraction operations. The former is more relevant for hard rock projects, while the latter is much more relevant for brine projects. Water use in general is poorly understood, especially with respect to how groundwater is affected by brine extraction.
- Land requirements. Hard rock and clay deposits will be mined almost exclusively through open pit methods. requires large land areas for both actual extraction and for the disposal and storage of mine waste, or tailings. Continental brines require large areas of land for evaporation ponds.
- Requirements for mine waste management. This is very related to geologic characteristics and again, has strong impacts on land requirements. Waste rock and tailings management will also require strategies to address the safe storage of waste, both to avoid the risk of structural failure and pollution.
- The required energy input and resulting emissions from mining and processing of ores and brines, which are again largely determined by geologic characteristics such as grade, impurity levels and liberation size

- Biodiversity in extractive areas, including flora, fauna, wildlife and items of cultural significance. Deposits and projects in biodiverse hotspots are given particular attention.

Social Conditions

- Community acceptance of mining projects and resource projects in general
- Educated, prior and informed consent regarding specific Li projects that leads to a legitimate social license to operate in a given area
- The potential displacement of other industries or livelihoods in the area, either through physical or economic means
- The potential displacement of humans who need to relocate to make room for development of a project or infrastructure
- Social vulnerabilities due to environmental impacts such as water use or pollution
- *The location of projects on our near indigenous lands*
- History of or potential for civil unrest or violent conflict due to poor social and/or environmental conditions resulting from extraction
- Potentially negative attitudes to colonial and imperial legacies, as well as ongoing neo-imperialism and power imbalances related to extraction

Project Implementation, Infrastructure and Technology

- The capacity of a local and regional industrial ecosystem to support a project. Energy and transport infrastructure, as well as the availability of technical services and trades, are important to ensure successful production of extracted materials. There may be a need to build up infrastructure, often in remote and challenging areas.
- The availability of human talent. Due to the low importance of Li through most of industrialized time, the level of technical human expertise is particularly sparse. This is compounded by a potential shortage of expertise in the mining sector in general as demand for metals grows rapidly in the coming years.
- The onset of direct lithium extraction (DLE) technologies. DLE refers to a group of technologies used to recover Li from brines. DLE is already in use in some capacity at continental brine operations in conjunction with traditional evaporation. However, DLE is often seen as a technology that could provide large quantities of Li from geothermal and oilfield brines with a low land footprint and low water requirements. There are currently no pure DLE commercial operations functioning.

- Clay processing technology. There are no commercially operating clay operations today. The ability of planned and prospective operations to successfully produce useable Li from clay feedstocks and to scale this production is important
- Processing of lepidolite, petalite, jadarite and other non-spodumene minerals. Li from lepidolite and petalite sources is currently only used in non-battery applications. The integration of mineral processing with the rest of the value chain to achieve successful production in battery grade materials remains a major challenge.
- The reprocessing of mine tailings to economically obtain Li. This is relevant for both Li lost to tailings due to economic reasons during processing and for tailings from non-Li mining where there no attempt to extract the Li. The latter is particularly common in legacy tailings from tin mining and processing.

Local and National Governance

- The ability of a nation and region to provide stable governance and a predictable regulatory environment that adequately considers all factors in the above categories.
- The willingness and the ability of government institutions to provide support for projects through financial and/or regulatory means.
- Governance in terms of specific environmental and social areas that directly affect lithium production.

Geopolitical Considerations

- Potential conditions that could prevent saleable Li products from being traded and thus limiting overall supply
- Sanctions or restrictions that could decrease the ability of material and human resources needed for extraction to enter a country
- Future alliances or agreements amongst nation states that could limit the sale of Li for political or economic gain

Investment Conditions

- Willingness of investors to take on new projects with higher levels of risk.
- Li prices that are favourable in comparison to energy and other operating costs in the long term.

- Monetary support from governments to develop Li resources that otherwise might fail due to unfavourable financial conditions.

Time Dimension

- The ability of new projects to start production on schedule
- The time it takes for new projects to scale up to full production
- The risk of reduced production at any point during the life cycle
- The number of years that production will occur

3 Key Concerns by Grouping

Based the requirements identified in section 2, the key concerns for each grouping are listed below. Further information can be found in section 4 and in the supplementary excel file.

Australian Hard-Rock

Key Issues: How fast projects can be constructed and ramped up, how quickly good quality resources are being depleted, attracting labour and talent from other parts of the mining industry

African Hard-Rock

Key issues: Social licensing, governance concerns, environmental regulations, remote operations and limited supporting industry/transportation to get products to market

Asian Brines

Key Issues: Technology development, environmental issues affecting local populations

Asian Hard-Rock

Key Issues: Technology development, environmental issues affecting local populations, development of problematic ex-China deposits in Afghanistan and Russia

European Hard-Rock

Key Issues: Social acceptance of mining, the reduction of environmental impacts

European New-Tech

Key Issues: Development of economic technologies with low environmental and social consequences deemed acceptable to society

North American Hard-Rock

Key Issues: Social licensing and indigenous land use concerns, energy intensive extraction requirements

North American New-Tech

Key Issues: Development of economic technologies with low environmental and social consequences deemed acceptable to society, indigenous land use concerns, fair taxation and stable regulations

South American Brines

Key Issues: Water use, development and economic scale-up of technology, social licensing, fair taxation and stable regulations

South American Hard-Rock

Key Issues: Social licensing, environmental impacts, economic scale up of technologies

4 Scenario and Production Matrix of Each Group-Outlook Combination

Table 1: Storylines and resulting production for optimistic, probable and breakthrough scenarios across all regions

Grouping		***Optimistic Scenario***	***Probable Scenario***	***Breakthrough Scenario***
African Hard Rock	*Storyline*	The mining industry finds ways to address concerns across the African continent. Meaningful social licensing, fair involvement of local communities and supply chains and a concerted effort to address environmental issues all occur. Investment risks are either mitigated or accepted.	A failure to address key issues leads to an increasingly negative view of extraction and a failure to gain social license at most projects. Environmental degradation and perceived investment risks also contribute to much lower production.	Technology and unprecedented collaboration between industry, governments and society allows for production to dramatically expand.
	Production	Bikita continues production at current rate. Major projects At Manono (DRC) and Goulamina (Mali) start producing during the 2020s, along with smaller projects in Zimbabwe, Namibia and Ghana. Other projects begin producing in some capacity in the 2030s.	Bikita continues production at current rate. Manono and Goulamina are the only additional projects that come online.	The same projects and timelines occur as in the optimistic scenario, but production is doubled.
Australian Hard Rock	*Storyline*	The country holds a mindset geared towards not only continuing but expanding its role as a mining jurisdiction.	The country is limited by increasing environmental degradation, concerns over land use and inadequately addressed indigenous concerns.	Technological breakthroughs in mining and mineral processing allow for the country to increase output at a rapid rate, exploiting lower grade deposits with social buy in

				and low environmental limitations.
	Production	Production increases at a CAGR of 10% from 2021-2035; 5% from 2035-2040; Constant production thereafter.	Production increases at a CAGR of 7.5% from 2021-2035; 5% from 2035-2040; Constant production thereafter.	Production increases at a 12.5% each year until 2030, by 5% each year until 2040 and remains stable thereafter.
Asian Brines	*Storyline*	Environmental and social concerns in China do not measurably affect production. DLE technology increases production volumes but not in any significant way. High environmental inputs are either minimized or deemed necessary to increase production.	Social concerns around land use and environmental impacts persist. Localized opposition does not hinder production in a significant way but disrupts existing projects and discourages accelerated development of new deposits.	DLE technology allows for new projects to come into production and for existing projects to scale up production with reduced environmental inputs.
	Production	Production increases at a CAGR of 7.5% from 2021-2050.	Production increases at a CAGR of 5% from 2021-2050.	Production increases at A CAGR of 7.5% from 2021-2050 at Chinese operations. DLE projects in China and Mongolia begin in 2027, ramping up until 2030 when production remains constant.
Asian Hard Rock	*Storyline*	China manages to increase production at existing and new projects. High environmental inputs are either minimized or deemed as necessary to increase production.	Social concerns around land use and environmental impacts persist. Localized opposition does not hinder production in a significant way but disrupts existing projects and discourages accelerated	New technology and unprecedented geopolitical developments allow for production from deposits in Afghanistan and Russia.

			development of new deposits.	
	Production	Production increases at a CAGR of 7.5% from 2021-2050.	Production increases at a CAGR of 5% from 2021-2050.	Production increases at a CAGR of 7.5% from 2021-2050 at Chinese Operations. Russian deposits begin producing in 2030, with production from Afghan deposits beginning in 2032.
European Hard Rock	*Storyline*	Social licensing challenges are addressed at most, but not all, more advanced projects across Europe. Major political challenges in Jadar and Serbia are alleviated, with extensive consultation and reconciliation.	Adequate steps are not taken to bring Jadar into production. Social opposition to resource extraction in Europe accelerates, with very few projects gaining the required social license to be developed.	Mining projects achieve widespread license to operate, through increased social acceptance and significant technological development.
	Production	Smaller projects in Finland, Germany, Czechia, Spain and Portugal also start production before 2030. There is no production from France or the UK. Current Portugal production continues at the 2021 rate. First production at Jadar in occurs in 2029.	No production from Jadar. Smaller mines in Europe come into production at a delay.	Jadar starts first production in 2028. New projects in France, the UK and the Ukraine come into operation throughout the early 2030s.
European New Tech	*Storyline*	Widespread societal acceptance of projects. DLE technology progresses, but still faces some technological barriers.	There is not particularly strong social opposition to DLE projects, but a lack of economically feasible technologies blocks production.	DLE projects become seen as a low-footprint, socially acceptable alternative to brine or hard rock operations. This is coupled with breakthrough

				technological developments.
	Production	German DLE projects begin producing as planned in 2026. A major project or expansion comes into production every 4 years thereafter.	No production.	Production is double that in the optimistic scenario.
North American Hard Rock	*Storyline*	Social licensing addresses concerns in indigenous and other communities. Technological and economic feasibility of extraction across all operations. Government support	Environmental concerns not addressed adequately. Lower government support for projects. High production costs limit the number of projects that come online.	Widespread social acceptance is coupled with breakthroughs in extraction and mineral processing, with extraction from challenging deposits made possible in an environmentally feasible manner.
	Production	All projects in Canada and the USA start producing before the end of 2030.	Certain projects are delayed or do not produce at all.	Same as the optimistic scenario, but pre-2025 production increases by 50%, all production thereafter is doubled.
North American New Tech	*Storyline*	Mexican extraction does not face roadblocks due to successful collaboration between stakeholders involved. Environmental and indigenous concerns in Nevada are addressed. DLE technology progresses, but still faces barriers. Different stakeholders in Mexico come to agreement that allows for good governance,	Low opposition to DLE projects, but a lack of economically feasible technologies blocks production. Environmental and indigenous concerns in Nevada not adequately addressed, with a patchwork of temporary solutions leading to delayed and lowered production. Difficulty in reaching agreement between	DLE projects become seen as a low-footprint, socially acceptable alternative to brine or hard rock operations. This is coupled with breakthrough technological developments. Concerns in Mexico and Nevada are alleviated by meaningful collaboration amongst all stakeholders involved.

		project feasibility and appropriate attention given to environmental concerns.	government, industry and civil society in Mexico.	
	Production	Silver peak continues operating at current output. Major clay projects in Mexico (Sonora) and Nevada (Thacker Pass) come online. DLE projects do not become operational until 2030, providing increased output until 2040. Supply remains steady hereafter.	No DLE production. Output from Thacker Pass and Sonora comes with delays and at a reduced amount.	DLE projects begin to operate in 2025. This leads to a windfall of other DLE operations coming online. There is an exponential increase in DLE production from 2025 to 2035. Constant supply thereafter. The same output from Thacker Pass and Sonora as the optimistic scenario occurs.
South American Brines	*Storyline*	Environmental and social concerns are largely addressed. Governments create a stable regulatory environment that provides fair benefit to communities and the countries.	Political pushback, lack of water resources and failure of the industry to properly engage in social licensing results in much slower production growth.	Social licensing and good governance are coupled with breakthroughs in DLE technologies, which are then used to develop and scale up production at operations across Chile, Argentina and Bolivia.
	Production	Production increases at a CAGR of 10% from 2021-2040; 5% from 2040-2050	Production increases at a CAGR of 5% from 2021-2050; Constant production thereafter.	Production increases at a CAGR of 15% from 2021-2040; 5% from 2040-2045; Constant production thereafter.
South American Hard Rock	*Storyline*	Good social licensing. Technological feasibility of extraction from unique deposit at Falchani.	Social licensing challenges hinder production. Extraction at Falchani not technologically and/or socially feasible. Resources at Brazilian deposits	Significant steps in social licensing, with good resources and advanced extraction and processing technology.

			of lower quality than expected	
	Production	Brazilian projects all come into production, with some also undergoing further expansions. Falchani starts producing in 2030, with an expansion doubling output in 2038.	Brazilian projects all come into production, with fewer expansions and slower ramp-up times. Falchani does produce at any point.	Brazilian projects all come into production, with sizeable expansions, in addition to full production and further expansions at Falchani.

5 Supply Results by Grouping

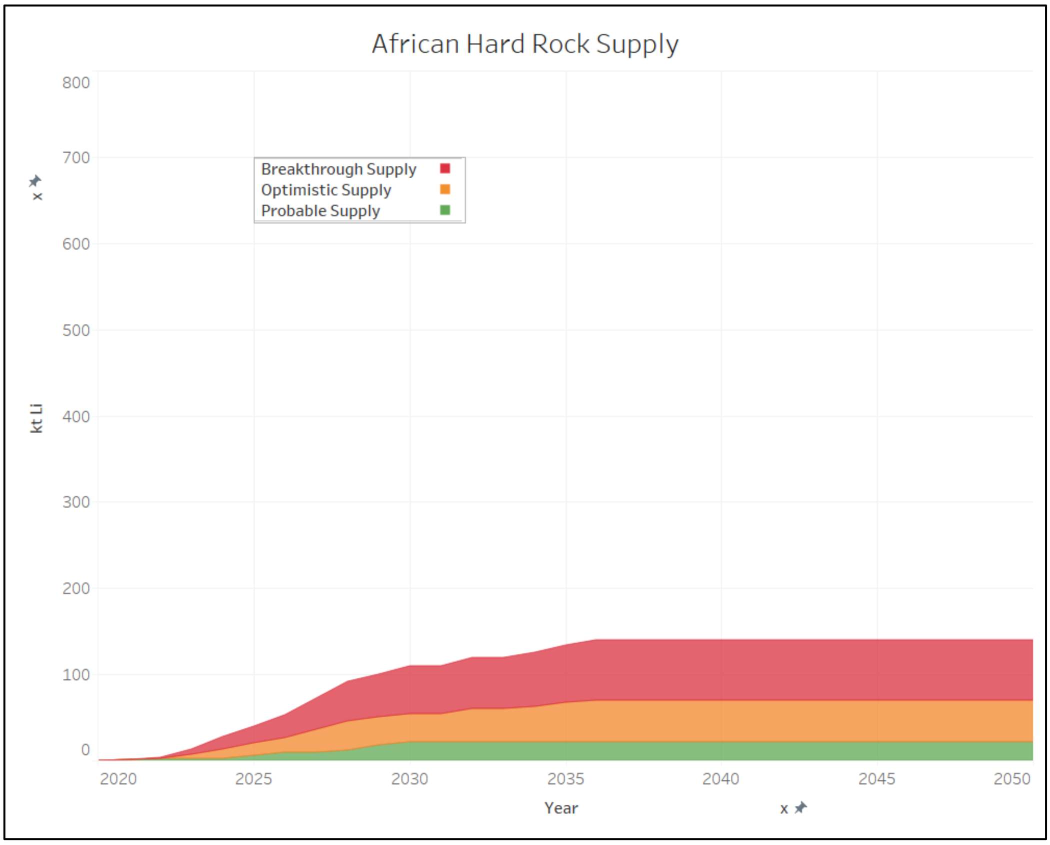

Figure 10: African Hard Rock Supply

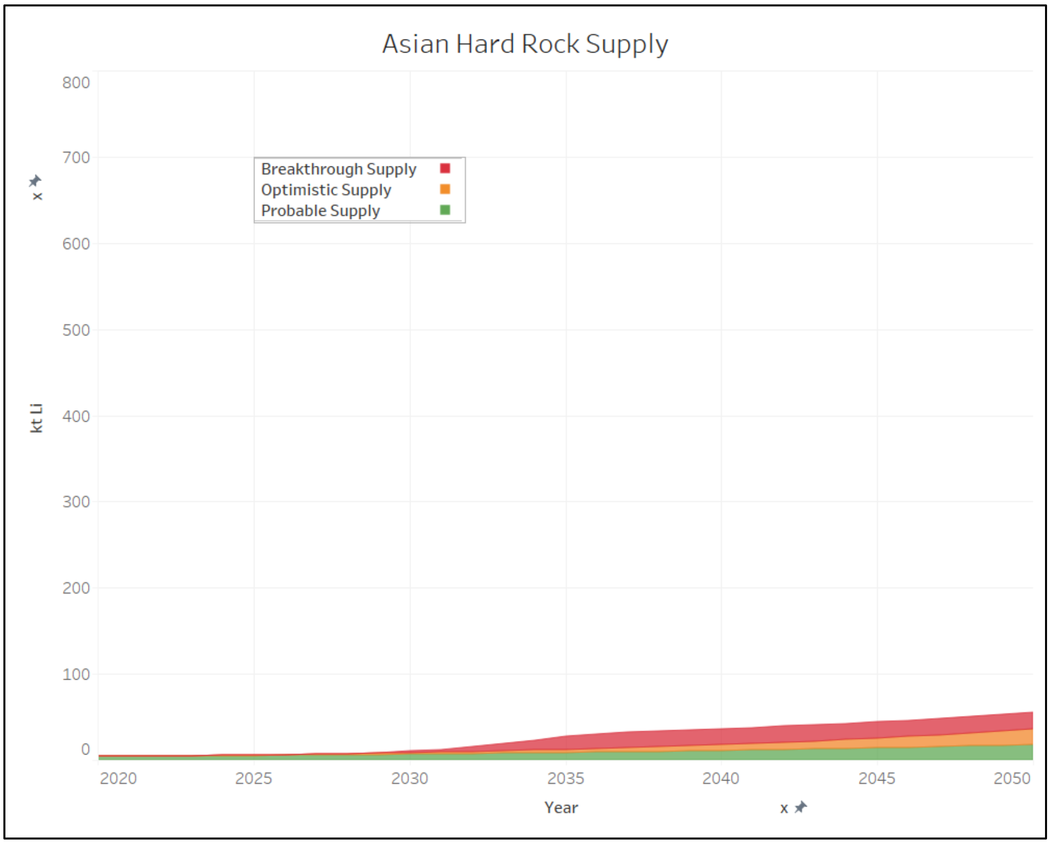

Figure 11: Asian Hard Rock Supply

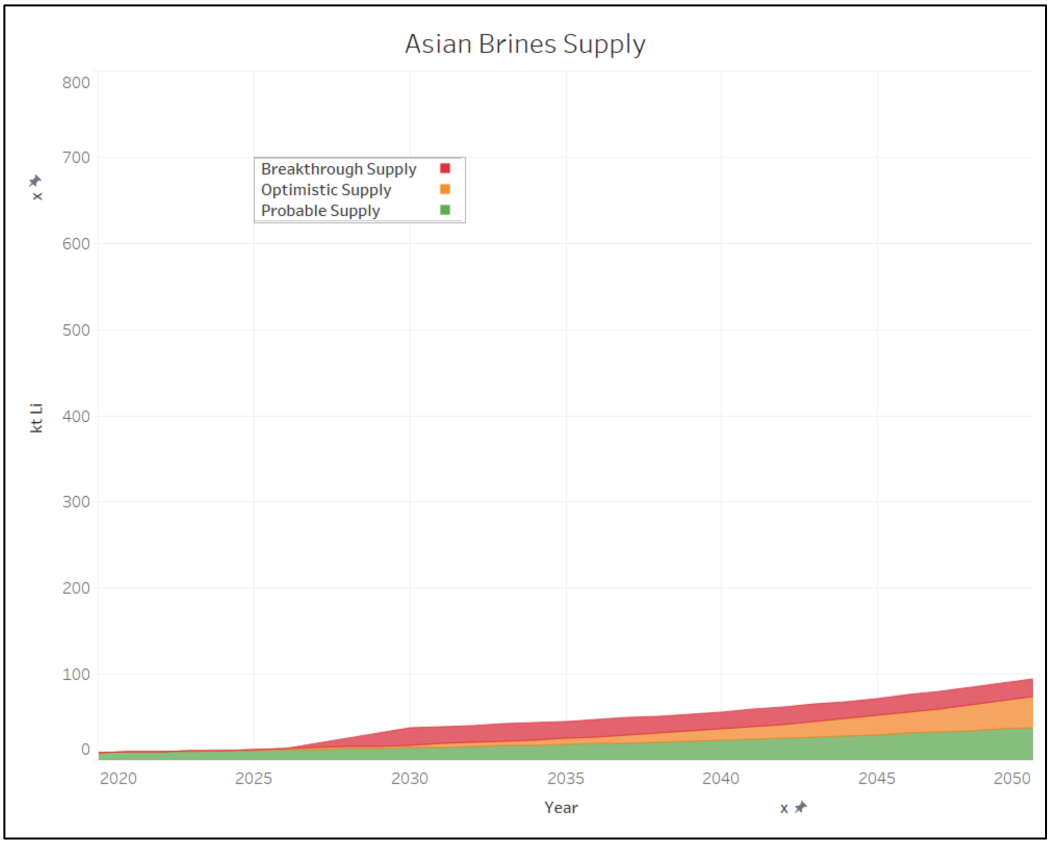

Figure 12: Asian Brines Supply

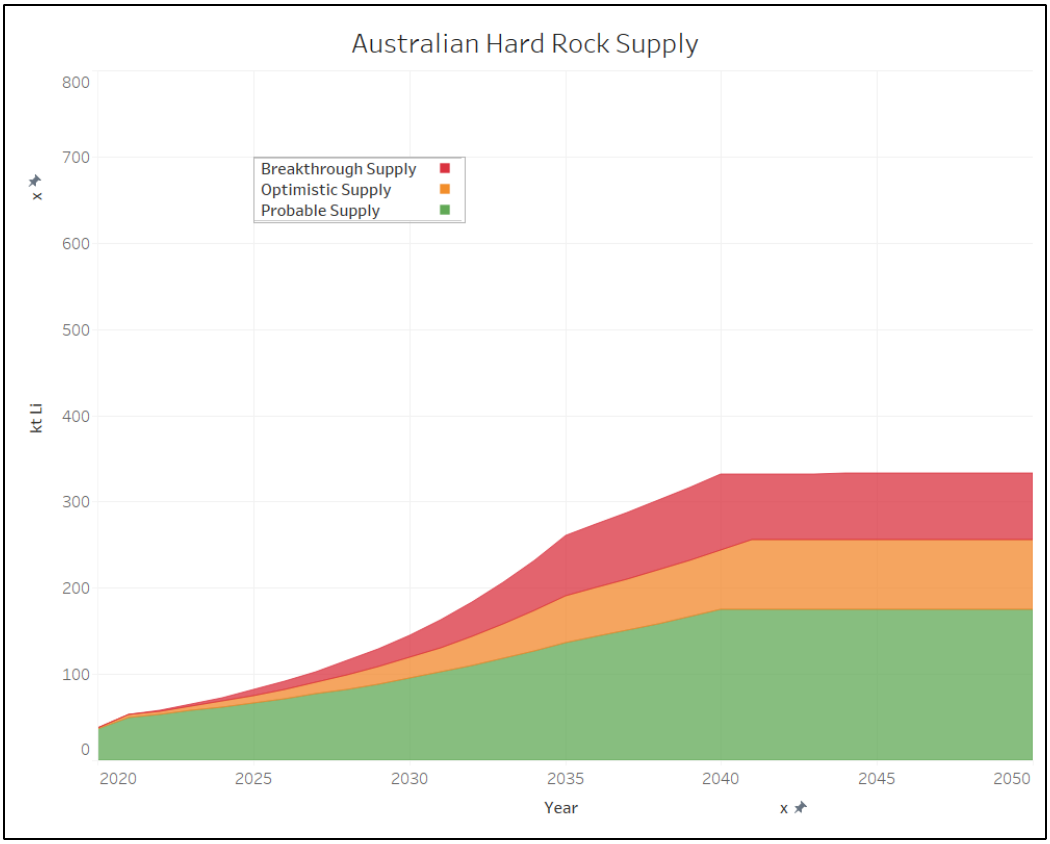

Figure 13: Australian Hard Rock Supply

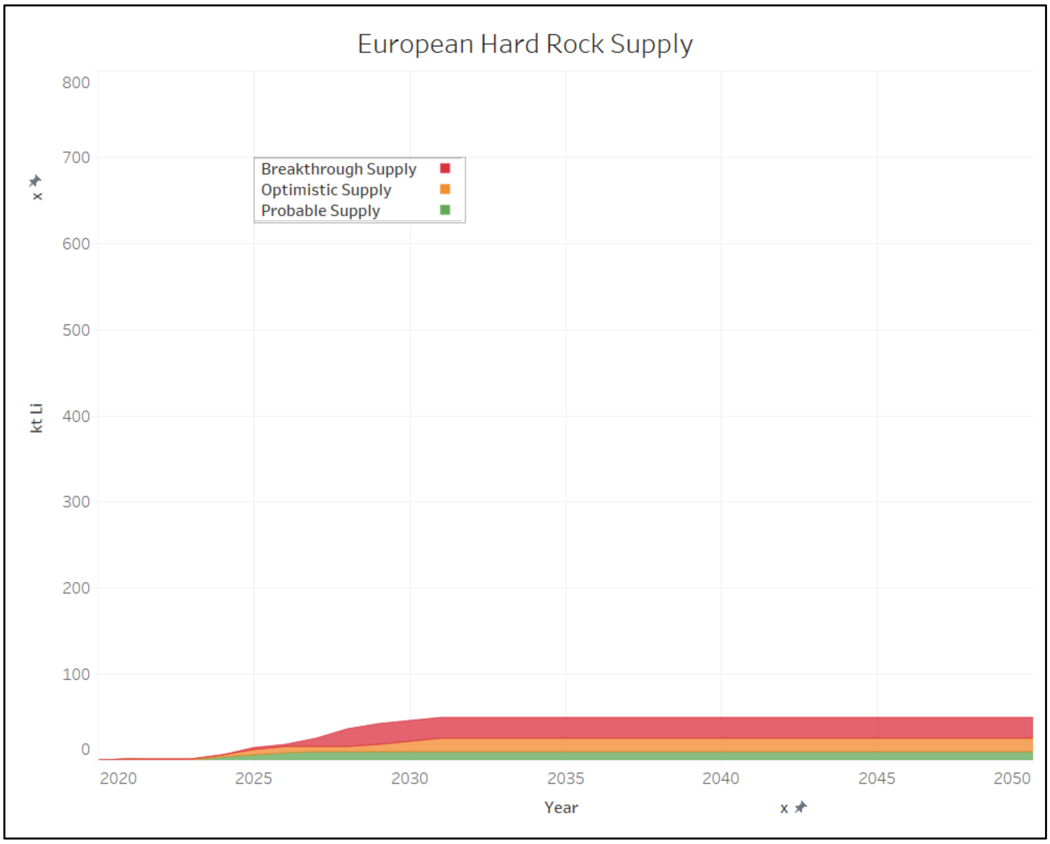

Figure 14: European Hard Rock Supply

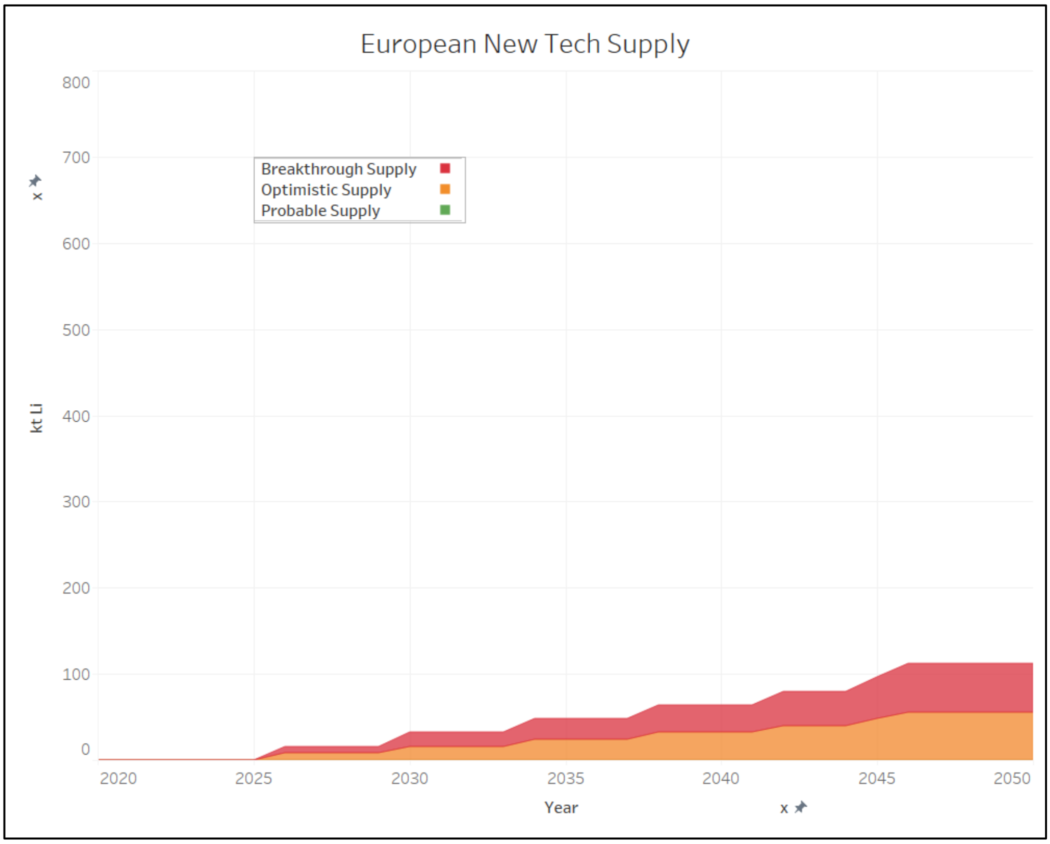

Figure 15: European New Tech Supply

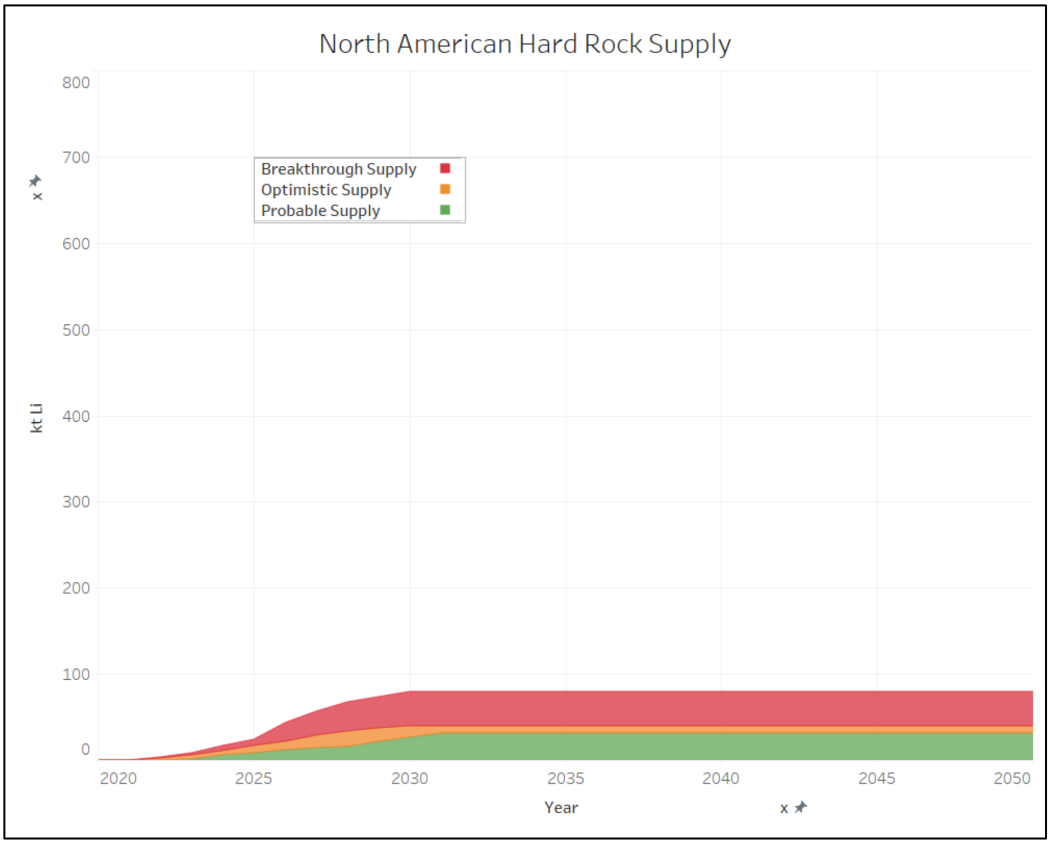

Figure 16: North American Hard Rock Supply

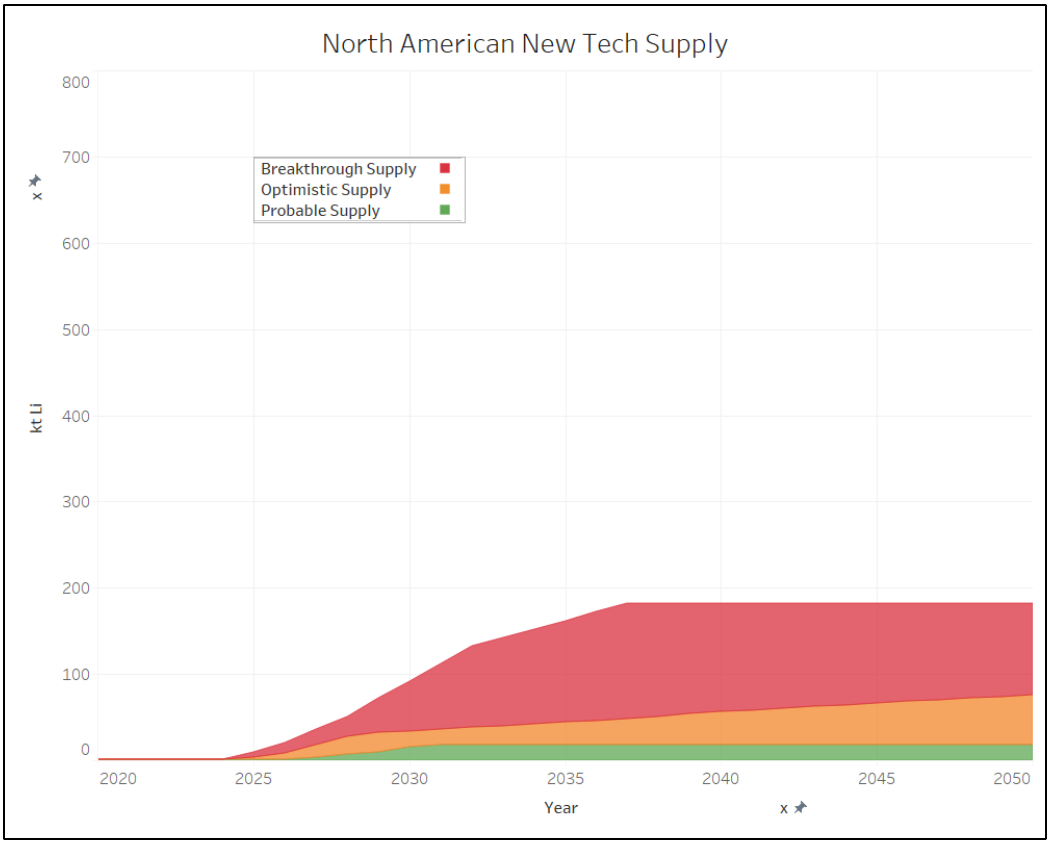

Figure 17: North American New Tech Supply

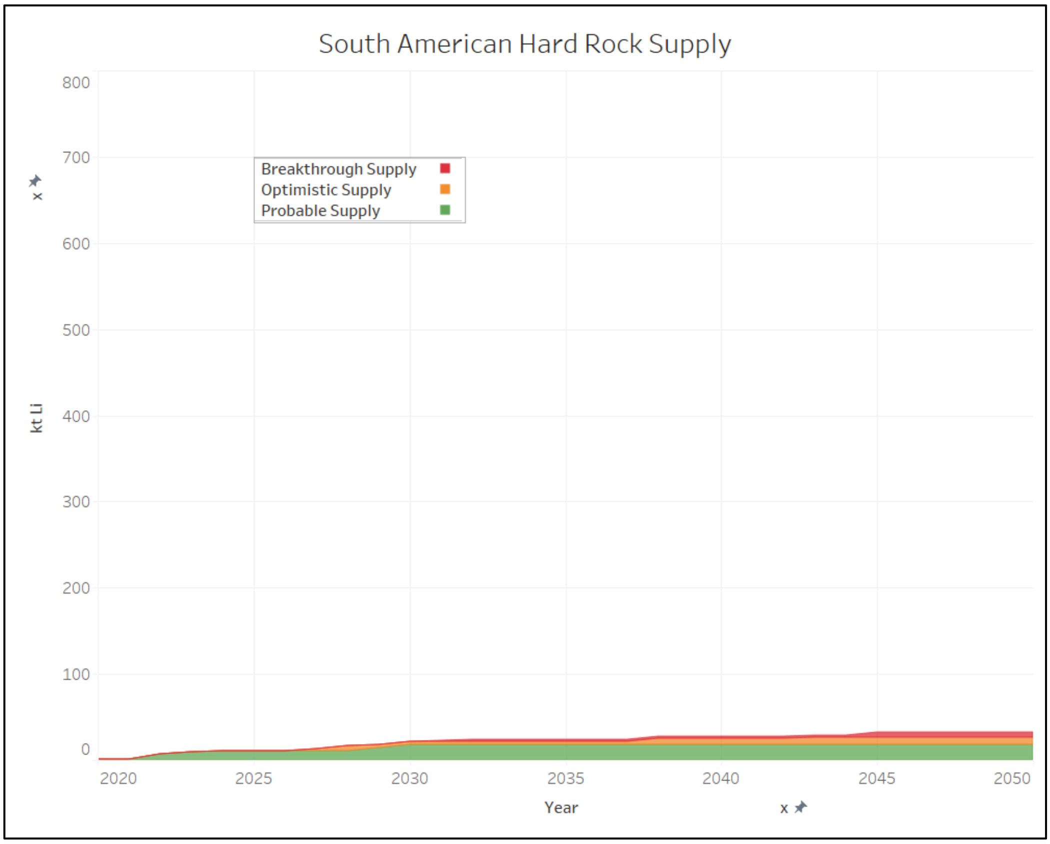

Figure 18: South American Hard Rock Supply

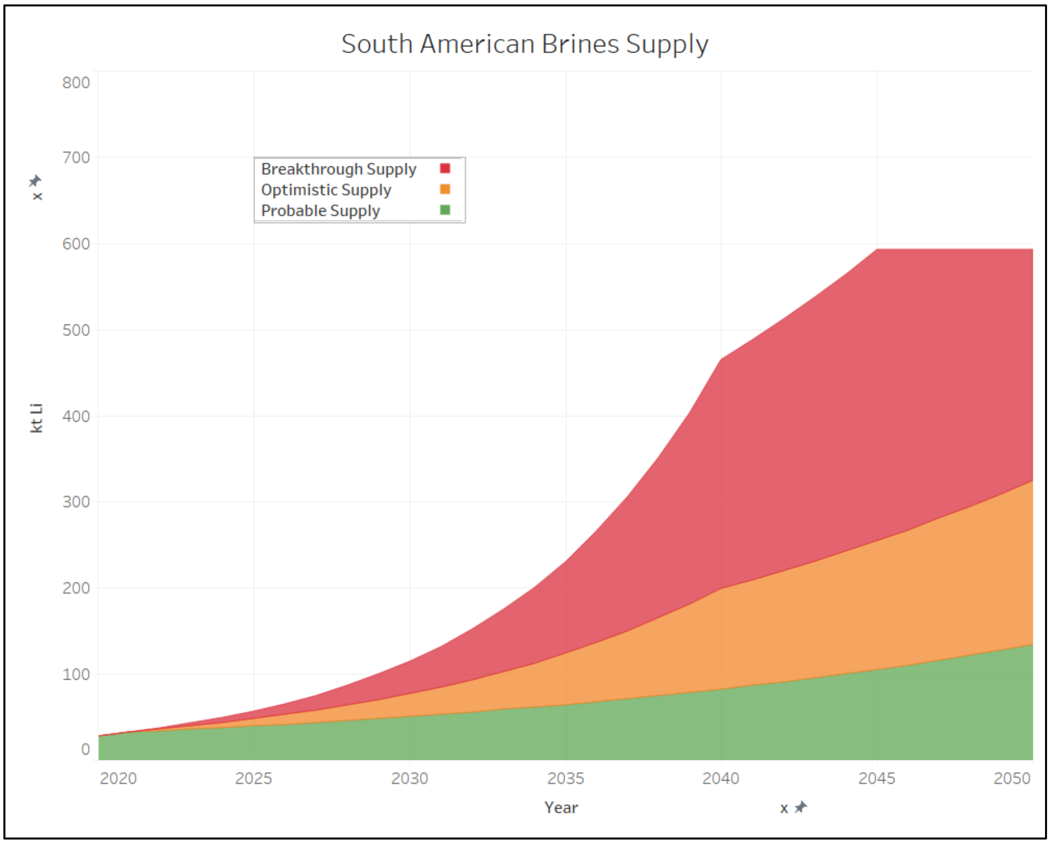

Figure 19: South American Brines Supply

6 Demand Scenario Results

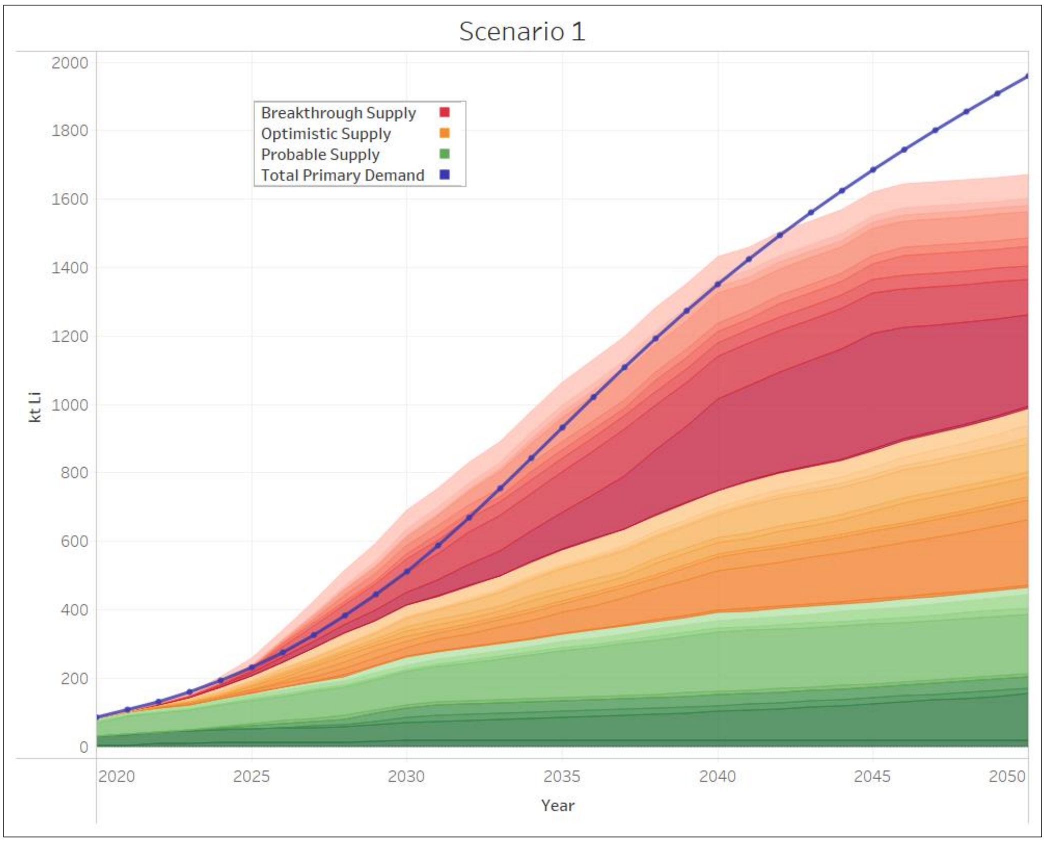

Figure 20: Demand Scenario 1

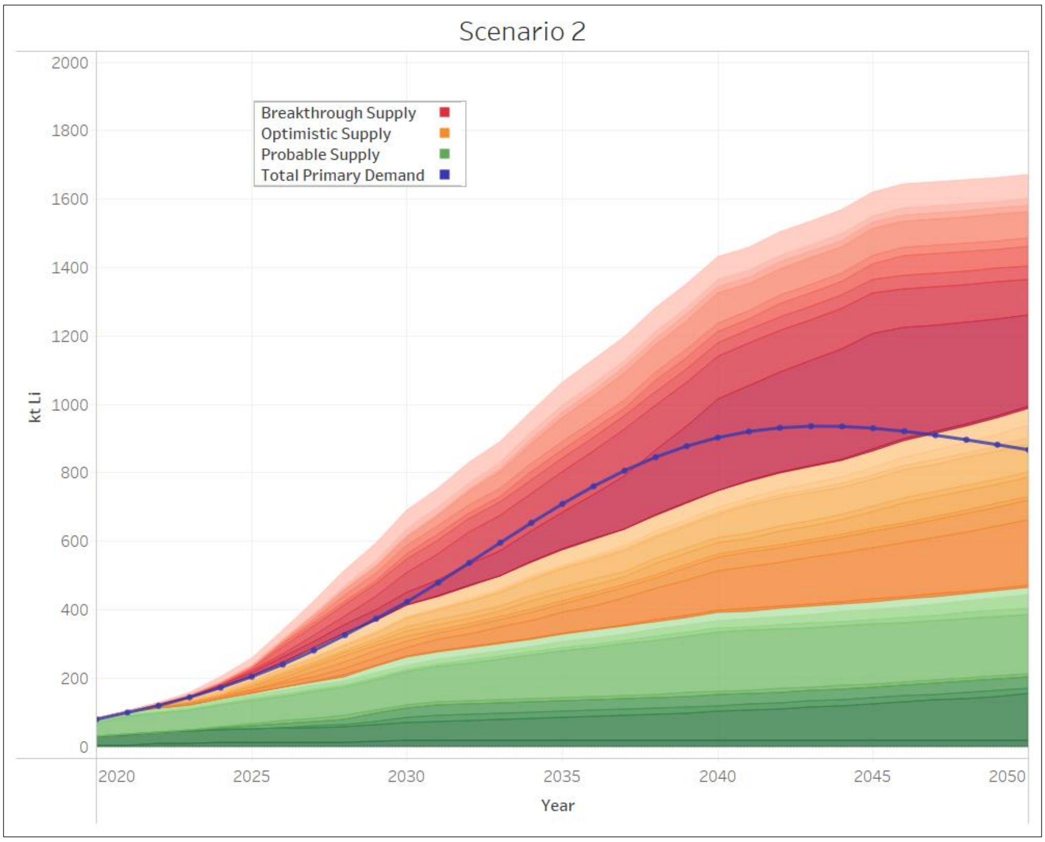

Figure 21: Demand Scenario 2

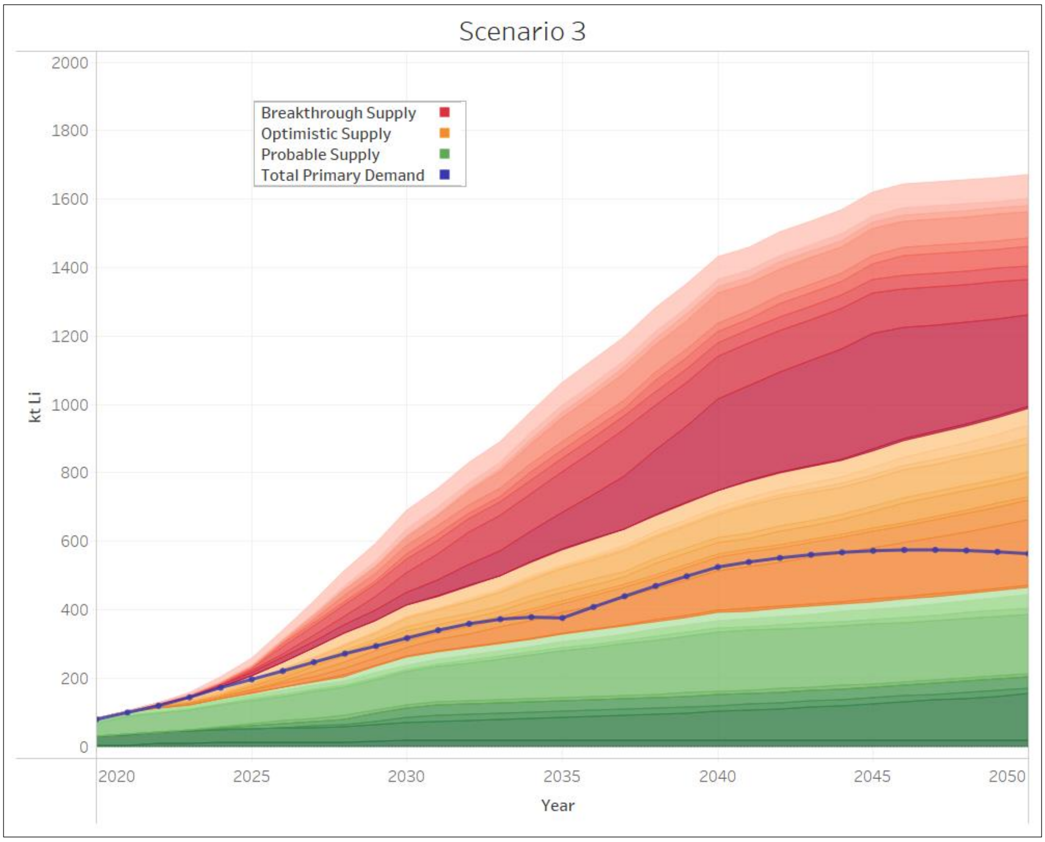

Figure 22: Scenario 3 Demand

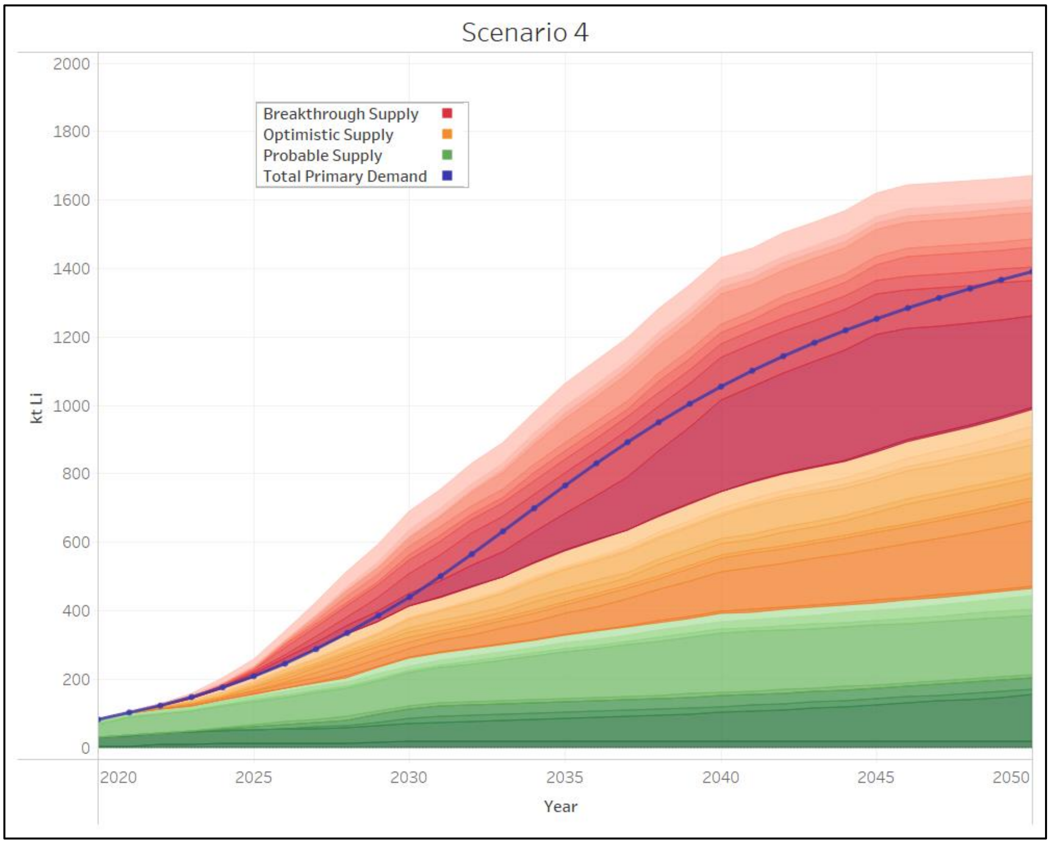

Figure 23: Scenario 4 Demand

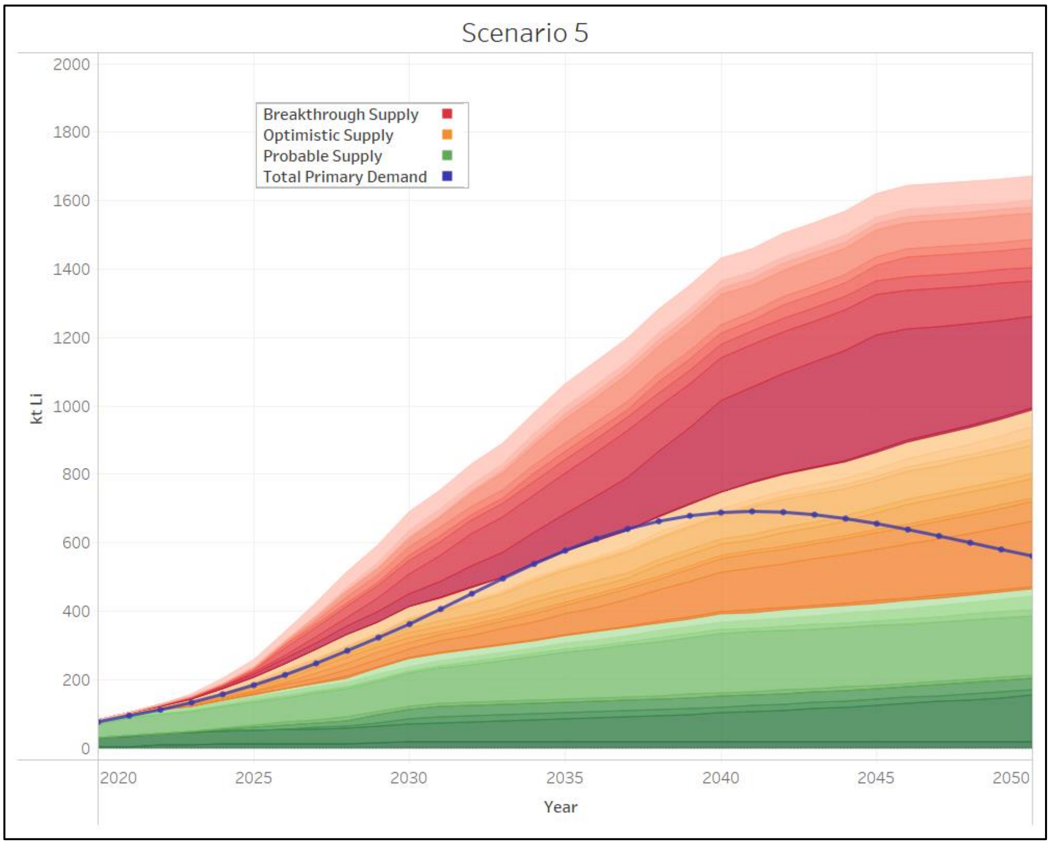

Figure 24: Scenario 5 Demand

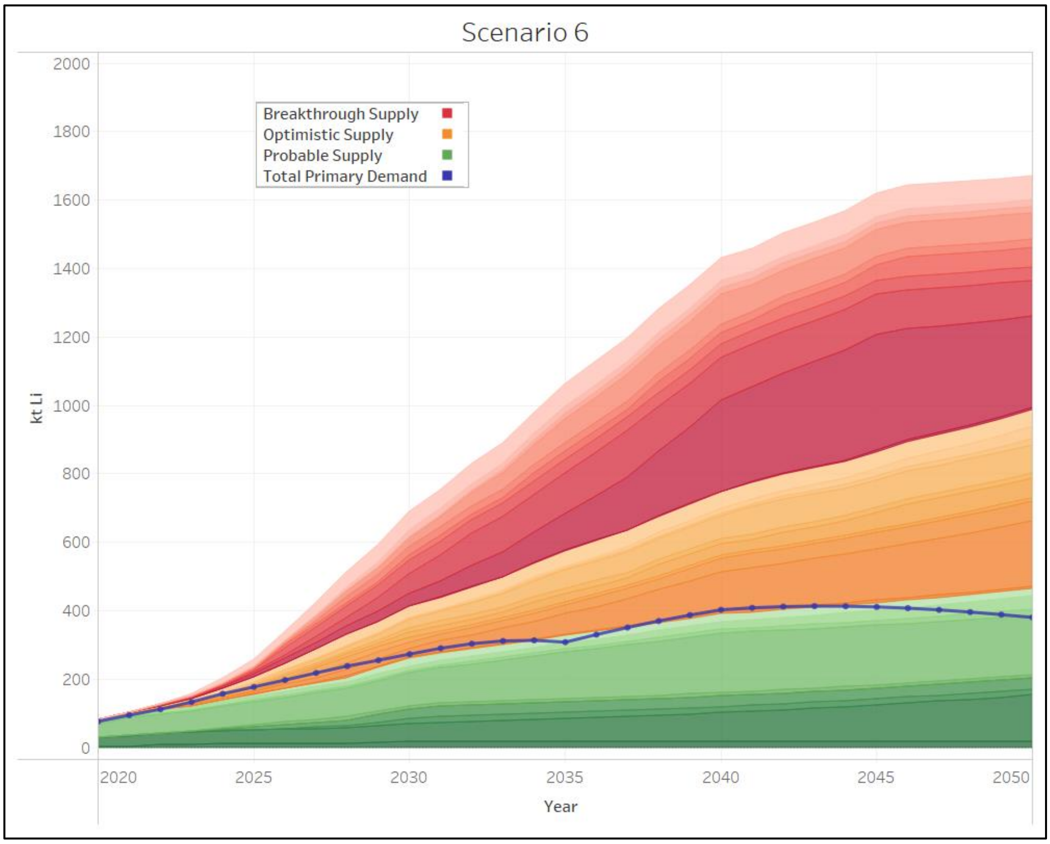

Figure 25: Scenario 6 Demand

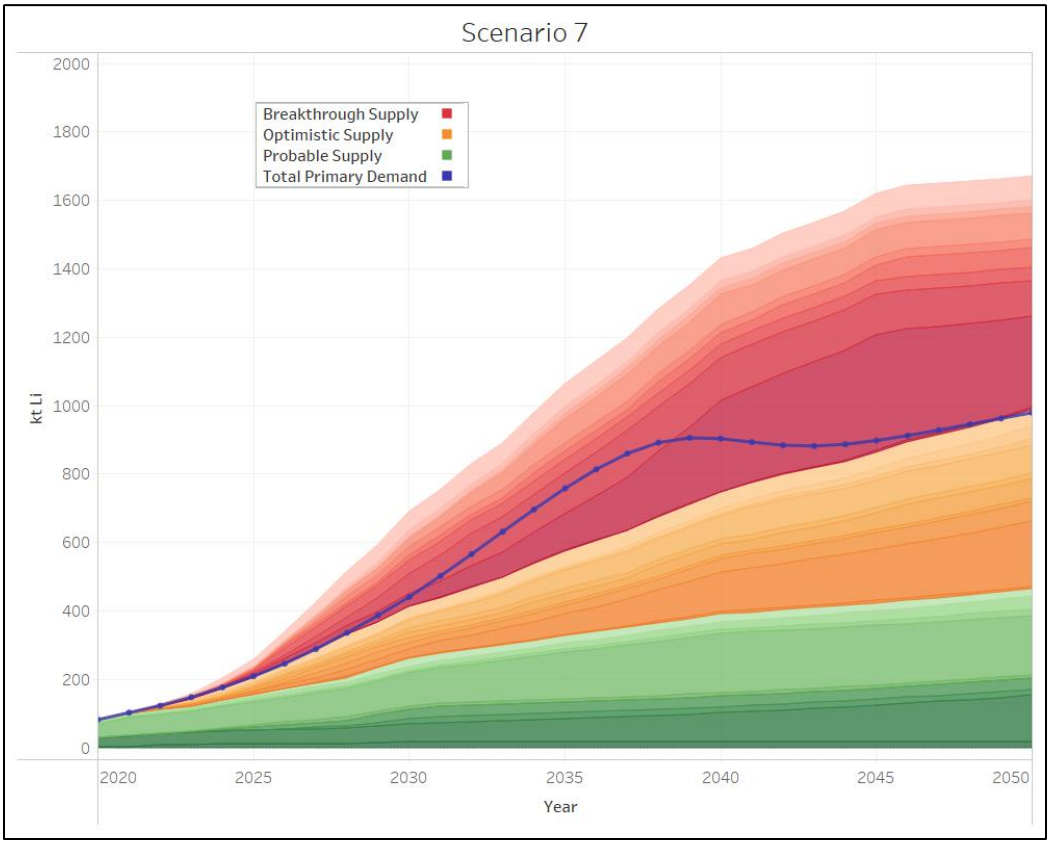

Figure 26: Scenario 7 Demand

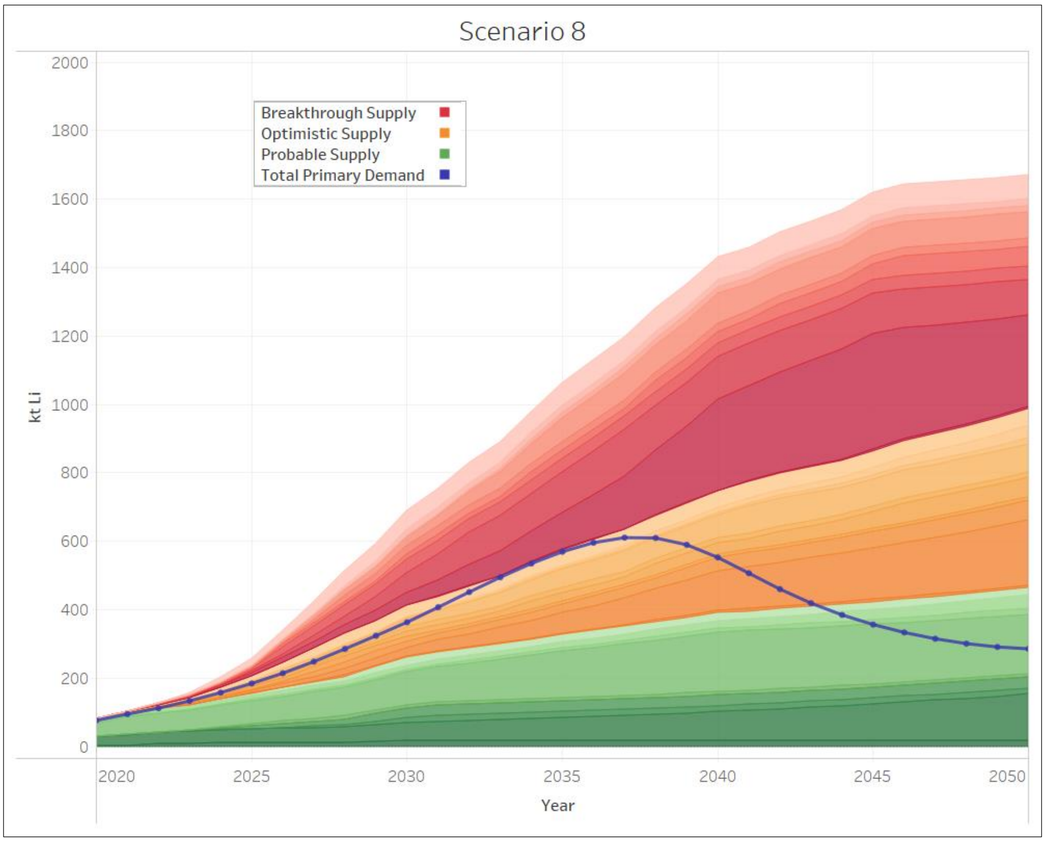

Figure 27: Scenario 8 Demand

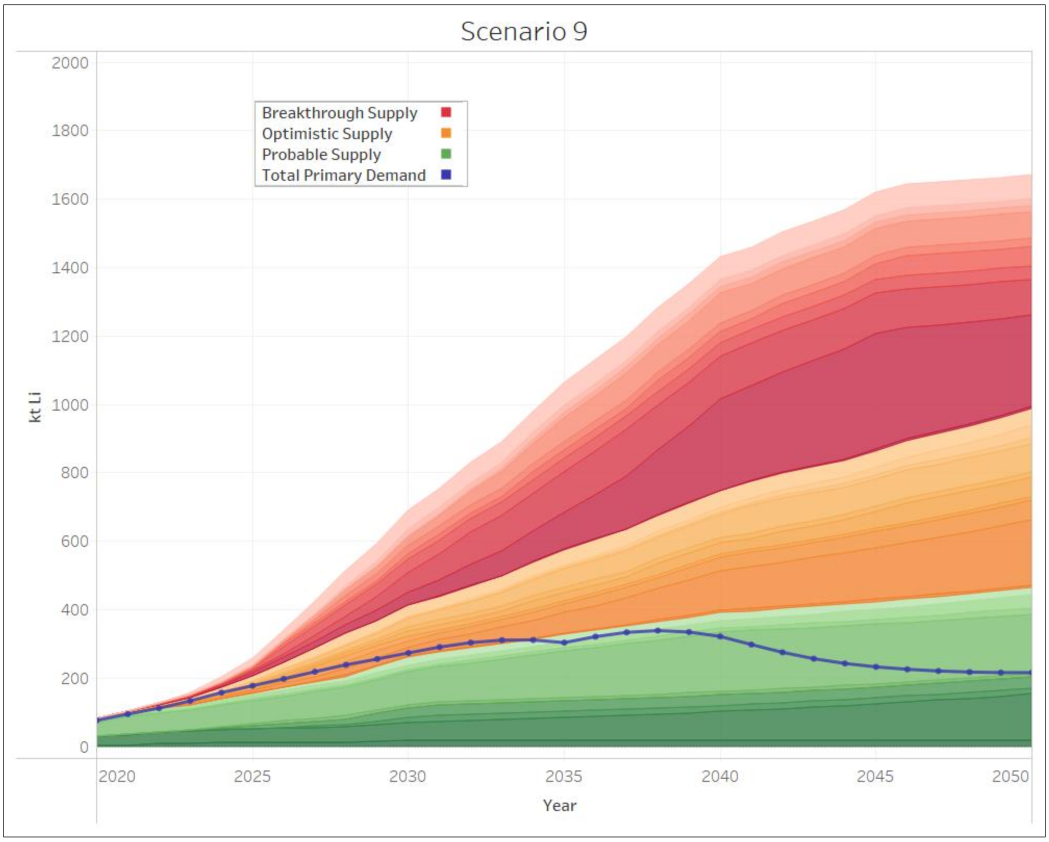

Figure 28: Scenario 9 Demand

7 Potential Stock Build-up Analysis

This analysis was run for scenarios 1, 2, 8 and 9. When the supply fails to meet demand, the simulation terminates and

Running the analysis for Scenario 1 (Figure 29) shows that, when considering stocks, there are no scenarios that can successfully meet demand for the entire model duration. This means that excess stocks in previous years are not sufficient to cover deficiencies in later years under any scenario.

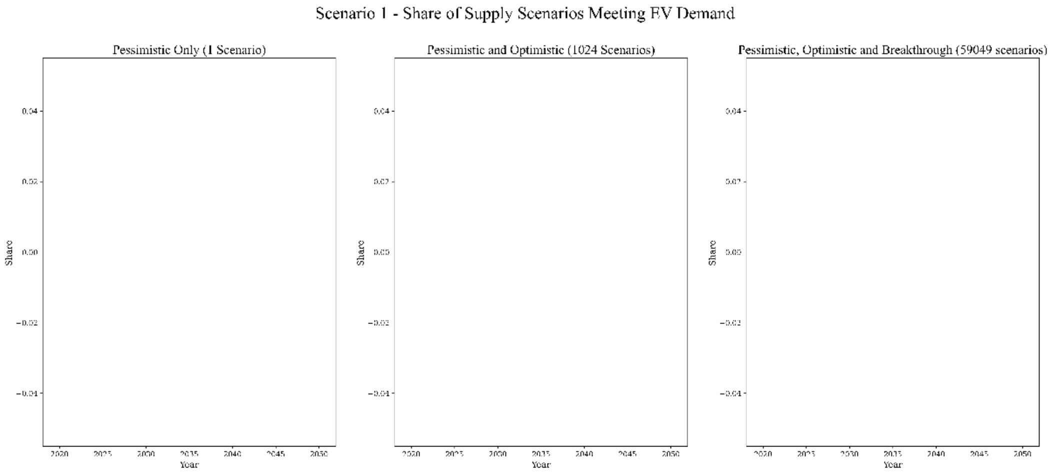

Figure 29: Share of supply scenarios meeting demand scenario 1

Moving to Scenarios 2, 8 and 9 (Figures 30, 31 and 32), the stock-buildup analysis shows results that do not differ significantly from the non-corrected model used in the study.

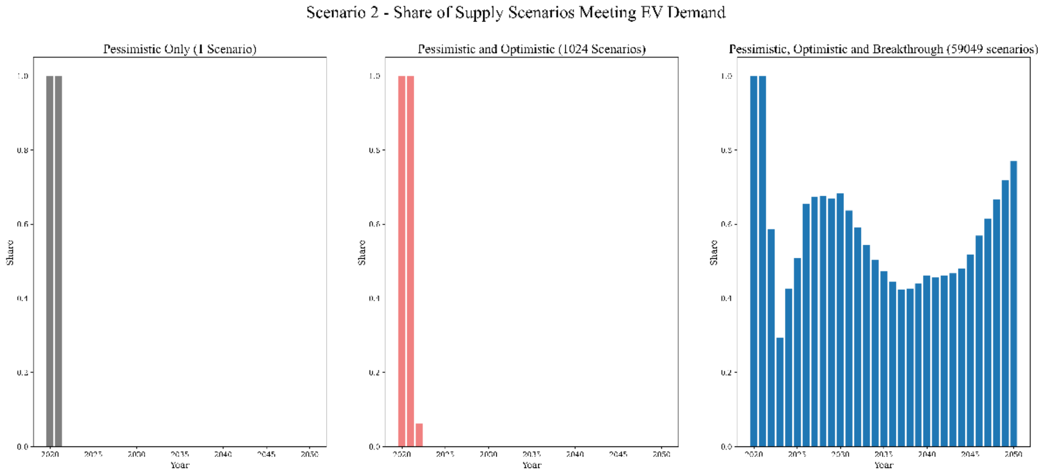

Figure 30: Share of supply scenarios meeting demand scenario 2

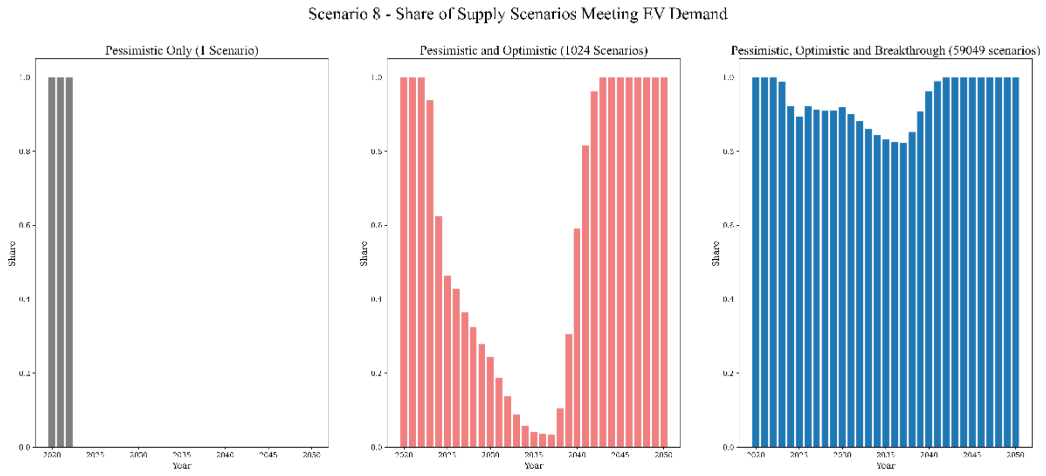

Figure 31: Share of supply scenarios meeting demand scenario 8

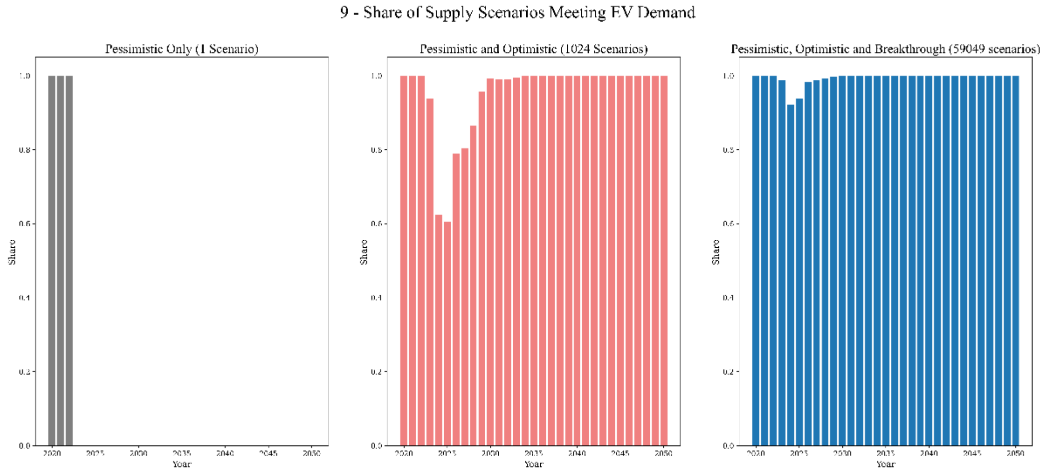

Figure 32: Share of supply scenarios meeting demand scenario 9

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